INDIAN ASTRONOMY IN THE GLOBAL CONTEXT

A VISION DOCUMENT

ASTRONOMICAL SOCIETY OF INDIA

भारतीय ज्योतिर्विज्ञान परिषद

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Contents

Foreword

The past two decades have witnessed major advancements in the area of Astronomy & Astrophysics thanks to large amounts of data from several advanced facilities comprising multi-wavelength space missions, wide-field surveys, multi-messenger mega projects, and the ever growing computing power and computational techniques. The Indian astronomy community has established itself as a key player in this global ascent with its own facilities as well as through participation in international endeavours, and utilisation of data obtained by international facilities. India's space observatory AstroSat, successfully launched in 2015, brought about a paradigm shift in Indian astronomy, opening the X-ray and Ultraviolet (UV) skies to the community. The Chandrayaan missions have provided a rich, unique dataset of our closest celestial body, the Moon. The recently launched solar space observatory Aditya-L1 is expected to provide a major boost to solar and heliospheric research in the country, and XPoSat will enable studying polarised radiation from nearby celestial sources. India is a partner in three major international projects, the Thirty Meter Telescope, the Square Kilometre Array Observatory and LIGO-India. With improved facilities, the community has also seen a steady growth in strength, reach and research output. These make this an ideal time for the community to reflect and chalk out its path for the future. The Astronomical Society of India (ASI) has enabled this through this Vision Document. This document accompanies two other vision documents for Indian A&A - the Mega Science Vision Document in A&A (MSV-2035) initiated by the Office of the Principal Scientific Advisor to the Government of India, and the vision document by the Indian Space Research Organisation (ISRO). MSV-2035 provides recommendations and priorities for mega-projects, both international and national, while ISRO's document focuses on the space sector. The ASI Vision Document takes a more holistic approach in its content, approach and ambition. It takes a comprehensive look at the entire breadth of Indian A&A, takes stock of the global key science questions and synthesises a vision for the future. It also addresses aspects related to growth of the community and its interaction with the society at large. Generated through an extensive and inclusive community-wide exercise, it is a document that reflects the aspirations of the Indian astronomers for the next decade and half, a document of the community, generated by the community, for the community.

Prof. Dipankar Banerjee,
President, Astronomical Society of India

Preface

The Astronomical Society of India (ASI), established in 1972, is the prime association of professional astronomers of primarily Indian origin. Beginning with a modest number of astronomers, the ASI, today has grown to be a body with about a thousand members. The annual meetings of the ASI have seen a steady growth in the number of participants, with the demography of the participants showing a large presence of young astronomers. To commemorate its Golden Jubilee year, the ASI initiated the generation of a Vision Document that reflects the aspirations of the country's astronomy community. Envisaged as a distributed effort, inputs were sought from active astronomy and astrophysics (A&A) practitioners of Indian origin, whether in India or abroad, from early career researchers to their senior most colleagues, and across all sub-disciplines. This document is thus an expression of the collective wisdom of the Indian astronomical community, of their aspirations and vision for development of A&A in India in the coming decades. A community-wide effort, this document reflects the vision of the A&A community, for the community, generated by the community. It is an articulation of what we, as a nationwide community, can achieve by appropriate prioritisation, coordination and planning, and the necessary policy and resourcing support from the relevant national agencies.

The generation of this vision document is very timely if not overdue. It comes two decades after the first such exercise was undertaken in 2004 under the auspices of the Indian Academy of Sciences (IAS). Since then, the A&A community, its capabilities, the resources and facilities at its disposal, as well as its output have grown many-fold. Today, India is a key partner in several major ongoing international A&A projects and A&A scientists of Indian origin have made a place for themselves in every domain of A&A. This vision document lays down a path for us to achieve our full potential in all areas of A&A – to do things in a manner that, as a community, we make the most of the resources we garner, complement efforts from across the country such that the whole goes well beyond the sum of its parts. On the one hand, this was a country-wide effort for introspection and exploration, learning about the work of colleagues from near and far, and on the other, of taking the global pulse of the various sub-domains; and then combining this information, keeping in mind the strengths and capabilities available within the country, to crystallise a bold but feasible vision for A&A for the next decades. It clearly articulates the short, medium and long term objectives without any prioritisation across sub-disciplines. It aims to make India a competitive A&A powerhouse, befitting its place and aspirations in the world in other domains spanning economics to politics and culture to science & technology.

The target audience of this document includes senior bureaucrats and science administrators from ministries of the Government of India, heads and senior management of institutions with a focus or interest in A&A along with A&A researchers and students at all stages of their career. We hope that our intended audience will find this document useful. This document, we also hope, will give young students a comprehensive, though succinct, view of Indian A&A and the excitement and promise which awaits those who choose to join this journey.

Despite its heft, this document is a summary of the more detailed articles which were written up for each of the subject areas covered here. They provide a more in-depth discussion and the justification for the recommendations given here. Each of these articles were drafted by a team of Working Group members led by two or more conveners who had also reached out to the larger community to seek inputs and feedback. A key landmark in this process was a discussion meeting held at the International Centre for Theoretical Sciences, Bengaluru titled “The Future of Indian Astronomy”, from 31 October to 02 November, 2022 in hybrid mode. This exercise has taken nearly two years to complete. We sincerely thank the entire Indian A&A community, especially the conveners of the various Working Groups, whose earnest, thoughtful and sustained efforts has made this enterprise possible. We seek to publish these articles as a collection in a special issue of the Journal of Astrophysics and Astronomy, which is co-published by the ASI.

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January 2024

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Executive Summary

Since the ancient times, India has been a pioneer in the field of astronomy. Great strides have been made in this field post-independence, with the progress accelerating substantially in the recent decades. In fact, some of the most impactful work of the 20$^{\text{th}}$ century came from Indian scientists. Today, India is home to a strong community of astrophysicists whose work spans an impressively large range, and to numerous facilities, both ground and space based, many of them internationally competitive. Across them, these facilities cover almost the entire range of electromagnetic spectrum as well other messengers of astronomical information like energetic particles. The upgraded Giant Metrewave Radio Telescope, for instance, stands out as the most sensitive instrument in its class. India's satellite missions, including AstroSat, Chandrayaan-3, Aditya-L1, and XPoSat, showcase its prowess in astronomy from space. India is actively participating in international mega-projects like the Thirty Meter Telescope (TMT) International Observatory, Square Kilometre Array (SKA) Observatory and Laser Interferometer Gravitational-Wave Observatory (LIGO-India), solidifying its position as a key player in the global astronomy and astrophysics (A&A) community. On the one hand continued investments, collaborations and capacity building will be essential to reap the benefits from India's investments in these and other national and international projects, and on the other the Indian A&A community now has the scale, the ability and the willingness that well planned collective effort can elevate us from being key contributors to leading players in strategically chosen areas.

This Vision Document summarises the outcome of a country wide effort to meet the Indian astronomy community's objectives for the next decade and half, or so. It makes a comprehensive assessment of our strengths, possible opportunities and aspirations, and synthesises a holistic vision for the future of A&A in India. It spans all sub-domains of A&A — from Heliophysics to Cosmology; observational as well as theoretical, and numerical modelling of astrophysical systems; setting up of observational and computational facilities; along with development of appropriate human resource. For each of these areas the document first sets the stage by briefly describing the national and international status of the field along with key questions of interest, and then lists short, medium and long term plans and recommendations. The guiding principles for these include strategic selection of focus areas such that they are well aligned with the existing and anticipated future strengths, and can lead to high impact science; crafting long term plans for developing core strengths in some key areas; and to seek and

utilise synergistic opportunities between different areas to amplify the returns from the resources and efforts expended. It also emphasises the importance of capacity building in terms of human resources and industry partnerships, and urges increased hiring of quality faculty and researchers. It encourages a strategic effort to lead global science using state-of-the-art instrumentation and promotes academia-industry partnerships for instrument and software development.

Recommendations

There are several recommendations made in the document that will enable development of core strengths in focused science areas, aligned with the current strengths as well as future goals of Indian A&A community. While some recommendations are very specific to a certain sub-domain, many are generic and are shared across all or many of the sub-domains. The era of multi-wavelength, multi-messenger astronomy makes access to large observing facilities through national and international collaborations, and to high-end computing facilities for Indian astronomers a strong focus of this document. Several key recommendations are provided here that will enable this during the coming decades. These recommendations are listed without prioritising, providing space for future developments arising from yet to be envisaged scientific and technological developments, and facilities in A&A.

- Cutting-edge science requires best-in-the-class data. It is essential for India to have access to the best multi-wavelength and multi-messenger observing facilities, through national and international collaborations and partnerships.

- Ensuring success of A&A mega science projects is essential for establishing India as an attractive and reliable partner for future endeavours. It is hence important to meet all the commitments (monetary and in-kind contributions) and provide deliverables of the required quality and in required quantity on-time over the full duration of the projects.

- There is a large gap between the largest optical telescopes (4m class) available in the country and the TMT, expected to be operational within a decade. It is essential to bridge this gap, both from the perspective of science, and technology development. An immediate short term requirement would be to obtain observing time on one of the existing international 10m class telescopes. In the longer term, having a national 10-12m class telescope (such as the proposed NLOT) is essential.

- It is important to enhance the capabilities of the upgraded GMRT (eGMRT) in order to continue to maintain it as a globally competitive facility at low radio frequencies. It is also an opportune time to setup some VLBI facilities across the country.

- There is a need to enhance our capabilities in multi-wavelength observations and expand to the sub-mm and γ-ray regimes. The expertise gained in the X-ray and Ultraviolet regimes through AstroSat and XPoSat needs to be nurtured and strengthened through new missions (such as the proposed INSIST (UV) and Daksha (X-ray) payloads).

- For an efficient use and increased science returns from the existing facilities, it is important to optimize and upgrade them. These would include adding new, state-of-the-art, instruments, automation and integration/networking of different telescopes, and implementation of dedicated, long term science projects such as spectroscopic surveys, etc.

- The success of the space solar observatory, Aditya-L1 needs to be carried forward. A natural successor would be a mission destined for the L4/L5. Given the challenges and science needs, a well planned technology development path needs to be charted in the short term to enable a scientifically capable mission on a decadal time scale.

- In contrast to the successes in space-based solar instrumentation, ground-based optical solar astronomy has been increasingly lagging behind the global state-of-the-art. A timely realisation of the proposed 2m NLST will provide the required complementary ground facility to the space missions.

- Exploiting the success of the Mars Orbiter Mission and the lunar Chandrayaan missions, further lunar and planetary missions can be planned in the form of in-situ, fly-by as well as sample return missions. This will propel India on the global platform in terms of the understanding of our cosmic neighbours as well as their interaction with the Sun, and enable us to explore the possibility of establishing facilities for astronomical research on the Moon.

- One of the fastest-growing areas of scientific explorations is the understanding of exoplanets. Still in its infancy in the country, this area of research can gain through the availability of specialised instruments and facilities. The proposed mega space mission 'Exoworlds' for analysing the atmospheres of extra-solar planets offers great promise for fulfilling the Indian as well as global needs for building an understanding of exoplanets.

- Cosmology is an area that has seen significant contributions from India, particularly in the theoretical aspects. Support for India led experiments such as CMB Bharat and PRATUSH will provide a strong boost to observational cosmology.

- Preserving dark skies for optical astronomy, and radio-quiet environment for radio telescopes is essential to enable these facilities to work to their design potential.

- A dedicated funding stream for exploring the development and demonstration of new-technology and proof-of-the-concept projects will be needed to resource many of the activities proposed here.

- Well-maintained data archives considerably enhance the scientific output from astronomical observations. It is strongly recommended that a centralized data archive be developed for all the Indian facilities.

- Large dedicated computing facilities are required to maximise scientific output from astronomical observations. More realistic simulations are needed to interpret the ever growing large datasets from observations. Setting up a national, high performance computing facility will yield the best results with optimum utilization of resources.

- Acquiring and nurturing suitable human resource at all levels is a pre-requisite to achieving the vision articulated here. There is a pressing need to establish departments of A&A in a larger number of science and technology research institutions and institutions of higher learning, and increase the number of A&A positions across all levels including faculty, research scientists, post-doctoral fellows and doctoral students.

- Capability building of the Indian A&A human resource by conducting suitable exposure camps, training programs, summer and winter schools and workshops targeting students and researchers at levels ranging from UG and PG students to ECRs and senior colleagues are essential.

- A&A is inherently inter-disciplinary in nature. It is evident that many different domains in A&A will benefit from setting up centers for inter-disciplinary research. While some of them might be focused on particularly vexing problems, e.g. space weather, others might be more generic and generate opportunities for cross-pollination.

- By providing the opportunity to the industry to work on challenging real life problems, often involving HPC, AI/ML and big-data, A&A has enormous potential for fruitful industry-academic collaborations and interactions, which needs to utilized optimally.

1 Science Goals

1.1 Solar and Heliospheric Physics

Earth is the only planet known to harbour life. Our home, and other solar system planets are gravitationally bound to our host star – the Sun – whose sphere of influence defines the heliosphere. Being close, the Sun is the only star whose activity can be observed at high spatial, temporal and spectral resolution enabling constraints on physical theories of plasma processes that are at play throughout the Universe. Exploring the Sun and heliospheric phenomena therefore is of fundamental interest.

The ultimate origin of the Sun's dynamic activity is due to a magnetohydrodynamic (MHD) dynamo mechanism operating in its interior. Solar magnetism originates due to complex, non-linear interactions between plasma flows and magnetic fields in the Sun's convection zone. How the interplay of small and large-scale fields and flows conspire together to produce solar magnetism and induce variability in the sunspot cycle still evades a complete, holistic explanation. Magnetic flux emergence and the subsequent evolution of surface magnetic fields govern the structuring and dynamics of the Sun's surface and outer atmosphere, comprising the chromosphere, transition region and the million degree corona. Magnetic fields acts as a reservoirs of energy, either directly heating the outer layers via magnetic reconnection or indirectly through the dissipation of MHD waves. Each process can heat the solar corona to a million degrees. Transients such as plasma jets can also directly inject mass and energy fluxes in to the outer layers. The coronal heating problem has now transitioned to understanding the relative contribution of each of these processes and identifying energy dissipation processes in the outer atmosphere. Imaging and spectroscopic observations play a very important role therein to constrain physical theories. Observations of the high latitude polar fields of the Sun remain an outstanding challenge due to large projection effects. Given the importance of the polar fields in seeding the future sunspot cycle, driving high latitude solar plasma winds and open flux which couple to the end of the heliosphere, polar field observations remain as one of the last great frontiers of the Sun.

Rapid restructuring of magnetic structures in the solar surface due to magnetic reconnection or MHD instabilities result in solar energetic events such as flares and coronal mass ejections (CMEs). They together create severe space weather – radiation hazards, energetic particle hazards and geomagnetic storms which impact the Earth's magnetosphere, upper atmosphere and space-reliant technologies humanity depends on. Constraining solar wind and near-Sun CME dynamics and their interplanetary evolution remain important space weather challenges both from the computational and observational perspectives. Solar radiation, energetic particles, plasma winds, and CMEs interact with planetary atmospheres and magnetospheres and perturb planetary space environments such as that of the Earth's resulting in geomagnetic storms that impact satellite based communication, navigation, electric power grids and other technologies. The heliosphere and the Sun-Earth system in this context is also a window to understanding such interactions in other exoplanetary systems underscoring the importance of these studies across other domains in astronomy and astrophysics.

Due to the multi-wavelength, multi-messenger nature of probing the solar electromagnetic radiation spectrum, energetic particles, magnetic fields and plasma flows, both ground- and space-based observations are crucial. The United States National Science Foundation has successfully commissioned the Daniel K. Inouye Solar Telesope, currently the world's largest solar telescope with a diameter of 4 m, while the European Union is in the process of building the 4.2 m class European Solar Telescope. In this context, India has not kept pace with the global solar observing facilities over the last half a century and has received a disproportionately low share of investment. Thus, development of new ground- and space-based observational facilities, active engagement with globally best-in-class observatories, along with supporting data analytics and computational modelling, infrastructure are key components via which the Indian community intends to address the outstanding challenges in solar and heliospheric physics.

Key Science Questions

What is the origin of the sunspots, quiet Sun and polar magnetic fields? How do convection and large-scale flows influence small- and large-scale magnetic fields? What is the nature of convection and plasma flows in the deep interior of the Sun? How do small- and large-scale plasma flows interact in the solar convection zone to produce solar magnetic fields and fluctuations in the solar dynamo mechanism, including extreme activity phases? How can we translate these knowledge for more accurate predictions of the sunspot cycle? How can we use novel helioseismic tools to set more

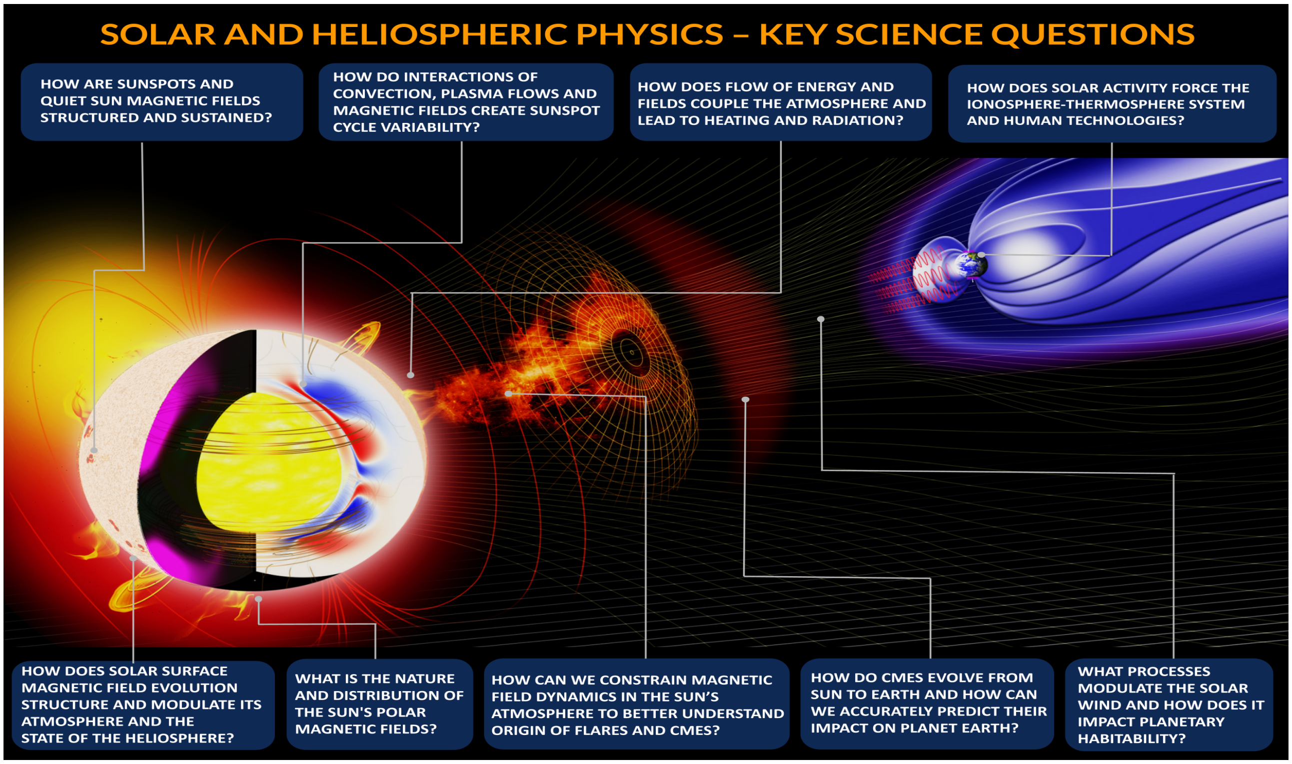

Figure 1: *An overview of the inner heliosphere – the Sun-Earth domain and the key scientific questions that are expected to drive the field of solar and heliospheric physics over the next decade or so.*

effective constraints on the Sun's internal magnetic field dynamics? How do magnetic fields that emerge on the surface govern the structure of the solar corona and the state of the heliosphere?

How do we constrain magnetic structures in different layers of the solar atmosphere to better understand initiation mechanisms of solar flares and coronal mass ejections? How are mass and energy transported through different layers of the solar atmosphere and how is this energy harnessed for sustaining high energy radiation and coronal heating?

How do CMEs originate, evolve through the heliosphere and what influences their geoeffectiveness (impact on Earth)? What physical processes drive and accelerate solar wind in the inner heliosphere and how do they shape the Earth's magnetosphere and influence the environment of the moon and other planets? How does the magnetosphere couple to the ionosphere and the thermosphere? How can this understanding be translated to better forecast the solar activity forced ionosphere and thermosphere? How do better constraints on Sun-Earth interactions inform our ability to appreciate the role of star-planet interactions in governing exoplanetary habitability? How can theory, data analytics and data driven MHD models of solar activity and Sun-Earth interactions be transitioned to operational space weather forecasting tools for societal benefit?

Recommendations

Ground-based facilities: Within the decade, a national 2-m class ground-based solar telescope is of high priority. Smaller telescopes capable of providing full-disk dopplergrams, magnetograms, infra-red or optical images of the Sun and coronagraphic images are required for their space weather value and providing global-scale context to solar space missions. User-base of currently existing radio facilities needs to be increased and avenues of complementary collaborations in this context should be explored to maximise the scientific utilization of existing and planned instruments.

Space-based facilities: Following Aditya-L1, there should be focused national efforts on the development of other missions.

- Mission to L4/L5 along with suitable experiments optimized for space weather studies.
- Out-of-ecliptic mission for polar observations.
- Low-earth-orbit missions with large telescope for studying the solar atmosphere in high resolution and for proof-of-concept missions such as a space-based magnetograph.
- Small-sat or cubesat missions for niche, specialized experiments, including space weather suite of instruments.

These missions are envisaged over the next decade or two, with their priorities determined by timeliness and complementarity to other national and international initiatives.

Computational facilities: To meet the growing needs of the solar and heliospheric physics community, we recommend a nationally networked, suite of high-end supercomputing facilities dedicated to computational astrophysics. Such a facility should not only be able to cater to our current requirements, but foresee future requirements in the next 10-15 years – having the capability of augmentation. National funding agencies should also explicitly allocate funds for individual proposals for computing time in existing government or private high performance computing facilities.

Capacity Building — Human Resource and Industry Partnerships: Given the increasing importance of solar and heliospheric physics research in the overall national and international context – including its high societal relevance – we recommend increased hiring of quality faculty and researchers to sustain India's strong leadership potential in this field. In addition to using Indian facilities, a strategically planned effort to actively pursue and lead science with the state-of-the-art instrumentation across the globe needs to be nurtured. Academia-industry partnership should be encouraged and emphasized in the development of new instruments, software and development of space weather related tools.

Societal Relevance — Translating Space Weather Research for Human Benefit: The Sun has a profound influence on technological infrastructure that sustain our modern society. Space weather impacts satellites, electric power grids, polar air-traffic and high frequency communications. Telecommunications and navigational systems are now almost completely dependent on Earth-orbiting satellites. Therefore, translation of space weather research for protection of space-based assets and extracting maximum societal benefit should be a high priority.

1.2 Solar System

Solar System is the only accessible place in the Universe that provides us with an opportunity to probe deeply into the working of planetary bodies and their interaction with the Sun. This is also the place where there is future for human expansion and habitats. Understanding the planets and small bodies and their evolution provides us with a solid reference for other similar systems beyond. Solar system science and exploration aims to address a very diverse set of bodies and processes through an equally diverse range of techniques. Crewed and un-crewed Lunar explorations, planetary explorations (remote sensing, in-situ and sample return), meteoritic studies and observations from Earth together form the means using which the origin, evolution, current state and future of the solar system is deciphered. It is currently well accepted that solar system bodies formed in a gas dominated disk around a young Sun. The specific sequence of early solar system events and time scales that led to the currently observed scenario are, however, either unknown or very poorly constrained. A holistic understanding of planetary formation and evolution requires comparative studies of the planets in our solar system and placing them in the context of the exo-planetary systems. Further, the search for exo-moons makes understanding our own Earth-Moon system a necessity.

High precision ($< 0.1\%$ level) isotopic studies of bulk samples and in-situ analyses along with morphological and mineralogical studies of the various components of different meteorites, extra-terrestrial samples (Mars, Moon, Venus, asteroids) are key to determine chronology and cause- causality relationship between the early solar system events and processes. Also important are high angular resolution observations of planetary disks such as by ALMA to test existing theories of the early stages of planetary formation. It is essential to relate the diversity in planetary disk environments and formation timescales to our current understanding of evolution in the solar system.

The geology and the evolutionary processes of solar system planetary bodies and their systems are quite diverse though there are commonalities in their overall characteristics. Missions to Mercury, Venus, Moon and Mars in the last decade have significantly enhanced our understanding of the rocky inner planets. While Voyager spacecrafts provided a glimpse of the outer planets, missions such as Cassini-Huygens, New Horizons and Juno have undertaken detailed studies of these environments. The ESA mission JUICE aims to study Jupiter and its three large icy Moons.

Planetary atmospheres play an important role in defining the environment as well as surface characteristics. These dynamic environments strongly respond to solar electromagnetic radiation and particles with localised and global effects at various time scales. UV spectroscopy helps in understanding the interplay of planetary magnetosphere and its connection with planet's auroral ionosphere. In addition, study of albedos in planetary atmospheres and interactions of moons with planetary rings/atmosphere can also be facilitated by these observations. Airless bodies such as Moon and Mercury have surface boundary exospheres that play a role as source and sink to atoms on the surface. The inner solar system planets have a secondary atmosphere whose formation time scales are not well constrained. Composition including isotopic ratios, atmospheric loss rate and paleoclimates inferred from surface measurements are all important to the evolutionary models of these secondary atmospheres.

The history of the solar system is built on lunar science. As the nearest solar system body that we can reach, explore, return material from, and hope to build a permanent base on, the relevance of lunar exploration has grown many fold in the last decade. Globally, the exploration of the Moon is undergoing a revival with sophisticated technologies of the new decade targeting two primary goals (i) lunar science (ii) Moon as a gateway for permanent settlement. The Indian Chandrayaan series of lunar missions have contributed significantly to this revival, with the highlight being the recent successful surface landing of the rover near the far side of the Moon. The Moon is increasingly seen as a base for astronomy, especially for low frequency (below 30 MHz) radio observations from the lunar farside and this is an area where India has not made significant strides yet. India's Gaganyaan missions, and its participation in the international Artemis programme that seeks to return humans to the Moon, will pave the way for a much larger exploration and the possibility of establishing facilities for astronomical research on the Moon.

Small bodies of the solar system are thought to be the repository of information from the time of formation of the solar system. This belief stems from the idea that being at far off distances from the Sun, for most of their orbits, they are less affected by solar radiation and hence preserve the records over time. Study of these bodies is therefore an important tool to study the evolution of the solar system. Minor objects uniquely provide information depending on their membership of various reservoirs such as the asteroid belt, the Kuiper belt, the Oort cloud etc. There have been several missions to small bodies, a majority of them to asteroids. A major challenge for this class of objects is the observed diversity in size, shape and composition. Given the large number of asteroids in the Solar System, ground observations are very important, particularly wide field surveys to detect Near Earth Objects and understand their origin and distribution.

Key Questions

At the large scales of the solar system, the main points sought to be addressed are: What were the constraints on initial conditions in the solar nebula? What was the chronology of events and processes during evolution to the present state? What were the sources and inventories of short lived now-extinct radionuclides (SLRs)? How and when did life originate? Is our solar system a unique stellar system with no identical twin in the galaxy/universe and if so why?

At more specific scales addressing the formation and evolution of the planets, some of the main questions are: what is the chronology of the first forming solids? What processes shaped/are shaping the surface geology of planets? How diverse is the surface composition (petrology, mineralogy and elemental abundances) and what led to this? What are the chances for past habitability and future habitation and the *in-situ* resources for this? What are the formation time scales of the inner planet secondary atmospheres? Do meteoric metals in its neutral form (Na and Mg), exist in the Venus and Mars atmospheres? Why is the southern aurora more intense (in terms of both emissions and temperature) than the northern aurora in the Jupiter?

The understanding of our satellite, the Moon is still quite superficial. Some of the main questions that can enable a better understanding are: What is the exact chronology of events that led to the formation of the Moon? What is the nature and duration of lunar volcanism and what are the sources of heat? Is the lunar farside crystalization sequence different from nearside? How diverse is lunar lithology? Did the young Moon generate a magnetic field and if so how What is the origin of lunar magnetic anomalies? How are lunar swirls associated to the magnetic anomalies? What is the source, sink and cycle of lunar volatiles? What is the internal structure and composition of the Moon? What are the mechanical and thermal conditions of the deep interior of the Moon? What causes seismic activity on the Moon? How does the dynamic heliospheric environment affect the near surface environment of the Moon?

In the study of small bodies, some of the key questions are related to their origin and distribution. What are the compositional and physical properties of minor bodies? What are the similarities and differences between different types of comets and asteroids? What is census of the Near Earth Objects (NEOs) and Potentially Hazardous Objects (PHOs); what risk do they pose to life on Earth?

Recommendations

Given the expertise with the country, three major leading themes are recommended: (i) Comparative planetary science (ii) Near Planetary Environments (iii) Small bodies including Near Earth Asteroids. Facilities and infrastructure required to enable cutting edge research in these broad areas are listed for a phase wise implementation in the 2023-2040 time frame. Additionally, active participation in international missions especially to Moon and Mars are essential if we are to establish a role in building human settlements. The technology development required in these programs provide an opportunity to be state of the art in a niche area thus contributing meaningfully to human endeavour.

2023–2028: 1. High-resolution spectrographs in the 3800–7000 Å on the larger telescopes in the country would be a major asset for cometary studies. 2. Data archival of existing observations would help in framing effective proposals. 3. A focused program for high energy observation of solar system bodies with ASTROSAT. 4. Next generation space based UV spectroscopy and imaging facility (such as the INSIST mission). 5. Miniature instruments for high precision measurements on rover/lander/balloon platforms. Especially important are balloon investigations at Venus where *in-situ* measurements of the lower atmosphere are critical. 6. Space qualified neutron detectors for spectral, temporal and spatial studies of the neutron spectrum in our solar system. 7. Participation in the international lunar geophysical network with seismometers. 8. Identification and preservation of analogue sites in India for planetary science and development of simulants. 9. Establishment and augmentation of dedicated laboratories with the state-of-the-art instrumentation.

2028-2035: 1. Simulated environments for test and characterisation of rovers and instruments (e.g. Venus). 2. Initiate building infrastructure for contamination free storage and analysis of extra terrestrial samples. 3. Initiate programmes to achieve considerable improvement in planetary instrumentation for compact, radiation hard (Jupiter) and extreme environment systems (e.g. surface of Venus). 4. A flyby mission to asteroids (multiple).

2035+: 1. Lunar sample return. 2. Venus atmospheric sample return. 3. Asteroid sample return. 4. Planetary Science Labs with storage facilities and high precision instrumentation.

1.3 Exoplanets

Exoplanets, also known as extrasolar planets, are planets that orbit stars other than our Sun. The study of exoplanets is one of the fastest-growing areas of scientific exploration, evolving from initial discoveries and characterizations to encompass demographics studies, atmospheric characterizations, planet dynamics and evolution, star-planet interactions, and the search for life beyond our solar system. In the coming years, the Indian exoplanet community is expected to grow as the field of exoplanet research is poised for a big transformation.

Studies have shown that planets are ubiquitous and on an average, each star in our galaxy harbours at least one planet. Moreover, smaller, rocky planets outnumber gas giants approximately by a factor of ten. Cooler M-type stars appear to have a propensity for hosting a larger number of planets as compared to solar, or G- type stars, and the majority of them are small rocky planets. Further, gas giant planets tend to be found more often around stars with higher metallicity ([Fe/H]) and are relatively younger, while small planet occurrence rates show less dependence on the host star's metallicity. The atmospheres of exoplanets are also being investigated to address a wide range of questions such as the diversity in compositions, and their variation with time, altitudes, latitudes, and longitudes. Further, studying the dynamics and evolution of planets is crucial for understanding the long-term orbital stability and fate of exoplanets. The cause, onset, and timescales of dynamical instabilities suggest that planets tend to form in compact multi-planet systems, eventually developing stable orbital architectures over billions of years through dynamical sculpting.

Stars and (exo)planets co-evolve, and their interactions significantly influence (exo)planetary habitability. Gravitational, radiation, magnetic, and stellar wind interactions play crucial roles in mediating the interaction between a planet, its host star and habitability. The search for habitable worlds involves identifying terrestrial planets with suitable conditions for life, determining their size and mass, and performing atmospheric characterisation to assess their habitability. The first step is to find terrestrial planets, which are predominantly rocky (1.6 Earth radii or $\sim$3 Earth masses). Currently, only around 40 such planets are known among the 5000+ confirmed exoplanets, with about 80% of them orbiting M-type stars and the rest around K-type stars.

Key Science Questions

How and why are the exoplanet properties (mass, radius, and orbital period) related to the properties of their host stars (spectral type, metallicity, age etc.)? If so, what can exoplanet demographics tell us about their natal environments and formation mechanisms? How common are Earth-like planets in the habitable zone of their stars? What are the evolutionary pathways of exoplanets based on their present atmospheric composition? What are the most effective approaches for incorporating clouds and haze in exoplanetary atmospheric retrieval models, and how can microphysics simulations offer valuable insights? What is the impact of photochemistry on temperature structures and spectra of these atmopsheres? How do we infer planet formation and early conditions from current exoplanet observations? How can we constrain the present exoplanetary system's history? How do close-in exoplanets modulate the activity of their host stars, and what are the observational signatures of this? Can this be used to constrain the stellar and planet properties? How does the interplay of intrinsic magnetism or magnetospheres of exoplanets and stellar magnetic fields, radiative, magnetic, and particle fluxes impact planetary atmospheric chemistry and mass loss? How does the activity of stars evolve over time, and how does this evolution shape planetary environments and atmospheres through external forcing? How do coupled star, exoplanet, and exo-moon systems interact and evolve? Ultimately, how do these physical interactions between a planet and a host star impact habitability? What are the unambiguous bio-signatures? Can they be present at detectable levels in the planet's atmosphere?

Recommendations

New and upcoming space and ground facilities in the future (e.g., GAIA, TESS, Nancy Grace Roman Space Telescope, PLATO, LUVOIR, HabX, and the ELTs) will offer many opportunities to the Indian exoplanet community for filling the gaps in exoplanet demographics as the current exoplanet surveys suffer from sensitivity limitations, making them incomplete. Characterising host stars using data from a combination of ground-based and space-based facilities would also be an important endeavour. The radial velocity follow-up observations of exoplanets detected by ongoing and future space-based transit (TESS, PLATO) and astrometry (Gaia) surveys is an important priority for the Indian community. Further, the synergy between atmospheric modelling and observations can be achieved through the

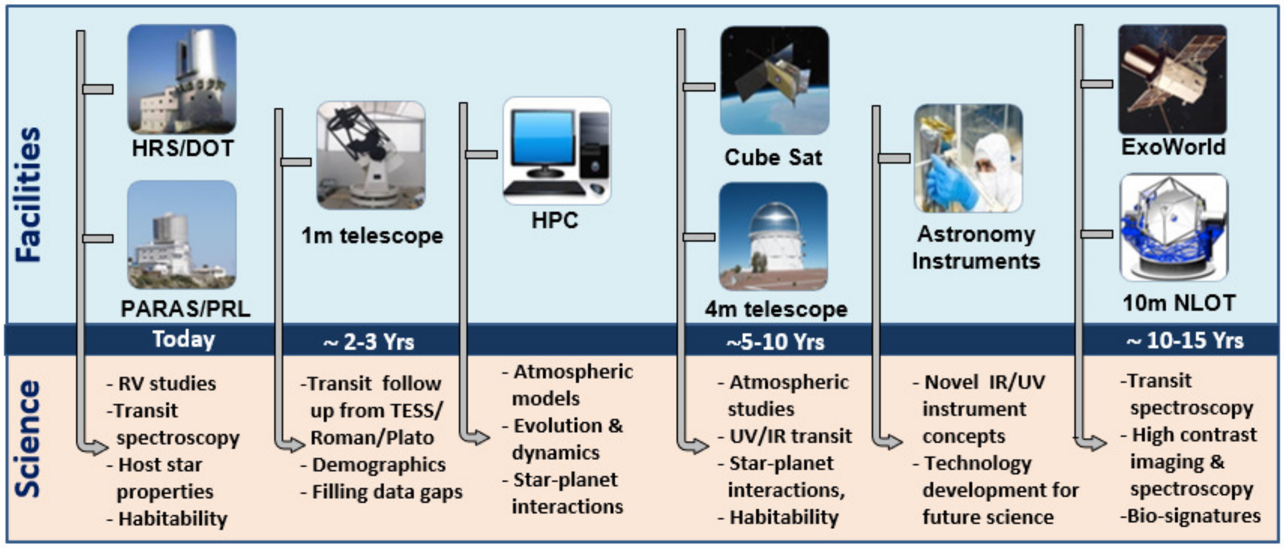

Figure 2: *Summary of key scientific goals of Indian exoplanet community: Existing and recommended facilities for future research.*

development of cutting-edge self-consistent 1D atmospheric radiative-convective equilibrium models coupled with cloud micro-physics, and expanding to 2D and 3D. Indian researchers would also like to develop expertise to study the evolution of exoplanetary atmospheres driven by interactions with their host stars. This entails developing large-scale multi-fluid models, coupled with stellar activity and atmospheric circulation models that incorporate atmospheric chemistry. In the pursuit of habitable planets, the development of state-of-the-art planetary atmosphere models could be prioritized along with a well-thought-out strategy to monitor a pre-selected sample of stars for several years using a high-precision RV spectrograph. In the long run, this approach can help to model the intrinsic variability of the star and potentially pave the way for the discovery of a second Earth.

Establishing a dedicated 4-meter class (or larger) telescope with an extremely precise radial velocity spectrograph ($R \geq 100,000$) within the next 5-10 years is of priority.

On the longer horizon of 10-15 years, a 10-12 meter, observatory class National Large Optical Telescope (NLOT) equipped with state-of-the-art instruments covering a wide range of wavelengths from near UV to thermal infrared is required. This facility will cater to a variety of exoplanet science goals, including high-resolution studies of solar system objects, probing exoplanet atmospheres for bio-signatures, and direct imaging of planet-forming regions.

ISRO's strengths can be leveraged in developing cost-effective exoplanet science and space missions. The proposed mega space mission Exoworlds for transit spectroscopy should be given the top priority. This mission holds great promise for fulfilling the long-term needs of the Indian community, extending beyond the 10-15 year horizon.

For immediate and interim needs that fall within the 5-10 year timeline, small satellite-based payloads can be built, such as a small transit mission in UV, optical, or IR, to do useful science in niche areas and also develop the required expertise in instrumentation, calibration, data analysis, and modelling.

A dedicated 1-meter class transit facility can be established for follow-up studies of space missions like TESS, PLATO, and the Nancy Grace Roman Telescope. By situating a facility in India, the data gap can be bridged in addition to conducting coordinated observations using multiple facilities across the globe.

The community can explore novel laboratory experiments and concepts for exoplanet observations from space and ground, including the strategies for accurate interpretation of spectra from solar system analogs. To demonstrate promising techniques/models, low-cost space experiments (e.g. Cube Sats) could be flown to planets in our solar system.

Establishing a centralised computational facility exclusively dedicated to exoplanet research is imperative for the Indian stakeholders. This specialised facility can be overseen and managed by experts in the field, offering a centralised platform where members of the exoplanet community can conveniently submit their simulations and computational tasks.

1.4 Interstellar Medium and Star Formation

The interstellar medium (ISM), the matter, radiation and magnetic field in the vast space between the stars, is a major constituent of the galaxies. For a Milky Way like galaxy, the ISM mass ($\sim 10^{10}\,M_{\odot}$) is about $10 - 15\%$ of the total stellar mass of the galaxy ($\sim 6 \times 10^{10}\,M_{\odot}$), and molecular clouds can be viewed as the fundamental ingredients of galaxies, as they are the channels that transform the diffuse atomic interstellar gas into stars. Observational studies of the molecular ISM have shown that it consists of structures over a wide range of sizes and densities, ranging from giant molecular clouds and filaments on large scales (100 pc -10 pc) to cores and protostellar disks (0.1 pc -0.001 pc) on the small scales. Fragmentation of the filamentary structures leads to the formation of dense and cold prestellar cores, which eventually evolve into protostars. Due to the range of scales involved and the fact that molecular clouds are highly dynamic in nature, star formation in molecular clouds is inherently a multi-scale phenomenon with different physical processes (e.g., gravity, turbulence, magnetic fields, and stellar feedback) having the potential to govern the outcome at different scales.

While the role of gravity and turbulence have been explored in the past, improved understanding based on polarimetric observations suggest that the magnetic fields play an important role in the formation of cloud substructure by setting preferred directions for large-scale gas flows in molecular clouds, and also directing the accretion of material onto star-forming filaments and hubs. Subsequent to the formation of a seed protostellar object, accretion as well as outflow are central to the question of assemblage of material from the envelope of the core to form stars. The process of protostellar evolution with the core is relatively well understood for the low mass stars as compared to their massive counterparts ($M_{*} > 8\ M_{\odot}$). The mass distribution of stars expressed as the stellar initial mass function (IMF) is a fundamental property of star formation, offering key insights into the physics driving the process as well as improving our understanding of stellar populations, their by-products, and their impact on the surrounding medium. Stellar IMF has shown that the massive stars correspond to only 1% of the stellar population. However, owing to their significant impact on their surroundings through injection of vast amounts of radiative and mechanical energy in the form of stellar winds, outflows, radiation pressure, photoionization and supernova explosions, the feedback from massive stars govern the star formation efficiency of molecular clouds. An additional challenge to the star formation studies lies in the fact that stars rarely form in isolation, and multiplicity is a ubiquitous

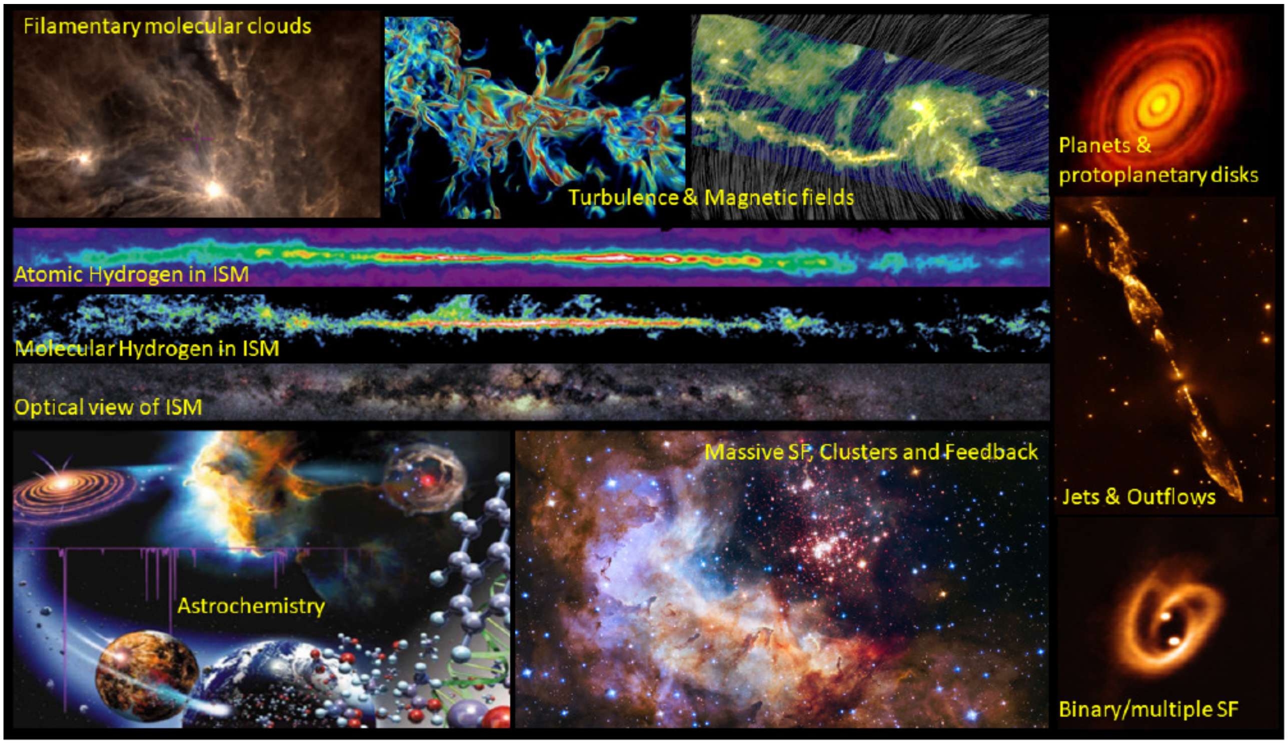

Figure 3: *A pictorial representation of the main topics of interest to the Indian community in the areas of the Interstellar Medium, Star and Planet Formation. The research involves understanding the physics and chemistry of how, starting from the diffuse atomic to molecular ISM, the filaments formed due to a combined effect of gravity, turbulence and magnetic field become the cradles of star and planet formation and how the stars thus formed impact their surroundings and subsequent generations of star formation. Figure generated using images available in public domain.*

feature across the H-R Diagram that deserves significant attention.

The detailed physical mechanisms that govern the formation process of a star, regulating the inward flow of gas onto the central protostar through disks, as well as the outward ejection of material in the form of jets and winds from the protostellar system still remain a mystery. Understanding the physical and chemical nature and the evolution of protoplanetary disks is essential to interpret the planet formation mechanisms and the demographics of the resulting planetary systems. The journey of gas from diffuse atomic through diffuse and dense molecular to protostellar and protoplanetary disks and planets is closely influenced by the astrochemistry occuring in it. Thus, the chemistry of the

ISM is intricately related to the initial compositions of planetary bodies, and are crucial to understand the origin of bio-molecules on planets like the Earth. The molecules detected in the ISM are (i) useful probes of the physical conditions and lifetimes of the environments and (ii) the building blocks of more complex molecules.

Key Science Questions

The key questions in the field of the ISM and star formation pertain to understanding the physical processes (turbulence, gravity, magnetic field) as well as the organization of material over length scales ranging from 0.001 to 100 pc. Some of the questions of interest to the community are listed below.

What is the relative distribution of gas in the different phases of the ISM, and whether the ratio of the gas in different phases is constant or evolving? How exactly does the accretion of matter occur in the filamentary environment from large-scale to the smallest scale? What is the role of turbulence at different scales in creating structures and star formation within them, relative to magnetic field and gravity? How does accretion proceed from envelope to disk and disk to protostar? How do massive stars form and how do they influence their environment towards the formation of the next generation of stars? What are the mechanisms responsible for the formation of multiple planet systems? How, when, and where are molecules produced and excited? What do they tell us about temperatures, densities, gas masses, ionization rates, radiation fields, and dynamics of the clouds?

Recommendations

The study of the ISM and the star formation processes require use of sub-mm observations which can probe such cold, dense environments, along with high-resolution infrared and radio facilities. The lack of such facilities in the country, particular in the sub- and millimeter bands, has led to Indian astronomers, over the last decade, basing their studies on archival data from international facilities. India recently got a 3.6m optical/near-infrared telescope and work on a 6-m sub-mm telescope project has just begun. While these facilities will provide the required data to some extent, to improve India's participation in cutting edge research problems pertaining to ISM and star formation, development of the state-of-the-art telescopes, back-end instruments, computational facilities and access to international facilities are recommended. These are elucidated below in terms of short-, mid- and long-term development plans.

Short-term recommendations: Upgrade of the existing 2-3m observing facilities in the optical/IR and enhancement of their capabilities by installing instruments such as polarimeters, high-resolution spectrometers, etc. Some of these instruments are already in the pipeline. Additionally, opportunities for participation as partners for international telescopes need to be explored at a national level to define modalities for India's membership.

Mid-term recommendations: (i) Development of multi-object ground- and space-based medium and high-resolution spectrographs in the UV (e.g. INSIST), optical (NLOT, TMT) and infrared (IRSIS), (ii) construction of 10-m telescope National Large Optical Telescope (NLOT) to bridge the gap between the existing 3.6-m DOT and the upcoming TMT and (iii) construction of a 10-20-m sub-mm telescope with wide-field mapping and polarimetric capabilities.

Long-term recommendations: (i) construction of high-resolution sub-mm/mm interferometric facility in India, for conducting spectroscopic, continuum, and polarization observations of dense molecular clouds. A facility capable of $\sim 0.01''$ angular resolution and $\sim 10\times$ greater sensitivity operating between 3mm to 2cm is also essential to identify close companions to stars at their earliest stages of star formation. (ii) Development of second generation instruments for the TMT capable of performing high-spatial resolution imaging and spectroscopy of young stars to detect close multiple components, study accretion and outflows and other properties towards the fainter end of the stellar mass spectrum in distant massive star forming regions residing in diverse environments.

1.5 Stars and Stellar Populations in the Milky Way Galaxy and its Neighbourhood

Stars are the fundamental units of galaxies and their investigation provides vital clues regarding the structure and evolution of galaxies. Our star, the Sun, is a main-sequence star fusing hydrogen to helium in its core. Its proximity allows for an in-depth study, that enables a comparison of its chemical composition with other stars in the Solar neighbourhood as well as across our Milky Way galaxy. Solar and stellar physics synergy has thus emerged as an important arena of research in the context of their chemical genealogy. Inspite of the hundreds of billions of stars in the Milky Way, what is known about their later evolutionary stages - sub-giants, red giant stars, horizontal branch stars (HB stars), asymptotic giant branch stars (AGB stars), post-asymptotic giant branch stars (pAGB), white dwarfs - is fairly limited. The evolutionary pathways of both single and multiple star systems continue to have several open problems. Some of the examples include Lithium-rich giants, how and when they are made and whether all stars go through this phase. The HB star morphology is different across globular clusters and while metallicity plays an important role, it appears that there are other factors at play. Another class of interesting objects is the set of hydrogen deficient stars found across many stellar evolutionary phases.

A galaxy is defined by the presence of its long-lived stellar population. Although dark matter plays a vital role in the hierarchical growth of galaxies, stars have been employed as fundamental tracers to address major milestones of galaxy evolution. The physics of galaxy formation, and the enigmatic nature of dark matter (DM) are two distinct but inter-wined phenomena. While the standard cosmological model provides a solution to these phenomena, a number of issues have emerged on galactic/sub-galactic scales. Our Galaxy, the Milky Way is a spiral galaxy with a prominent disk structure. It is known to host ~ 170 globular clusters and ~ 50 dwarf galaxies, and stellar streams that are known to exist within the 250 kpc, see Fig. 4. The vertical structure of a galactic disk is a good tracer of the disk potential and is crucial for understanding the vertical disk dynamics and evolution. A realistic, multi-component galactic disk model of the Milky Way has shown that the gas has a vertical constraining effect on the stellar disk in the inner Galaxy, while the DM halo has a constraining effect in the outer Galaxy. Stellar streams, that are narrow and dynamically cold, provide an important probe to unveil the invisible small-scale lumpiness in the DM distribution. A kinematic

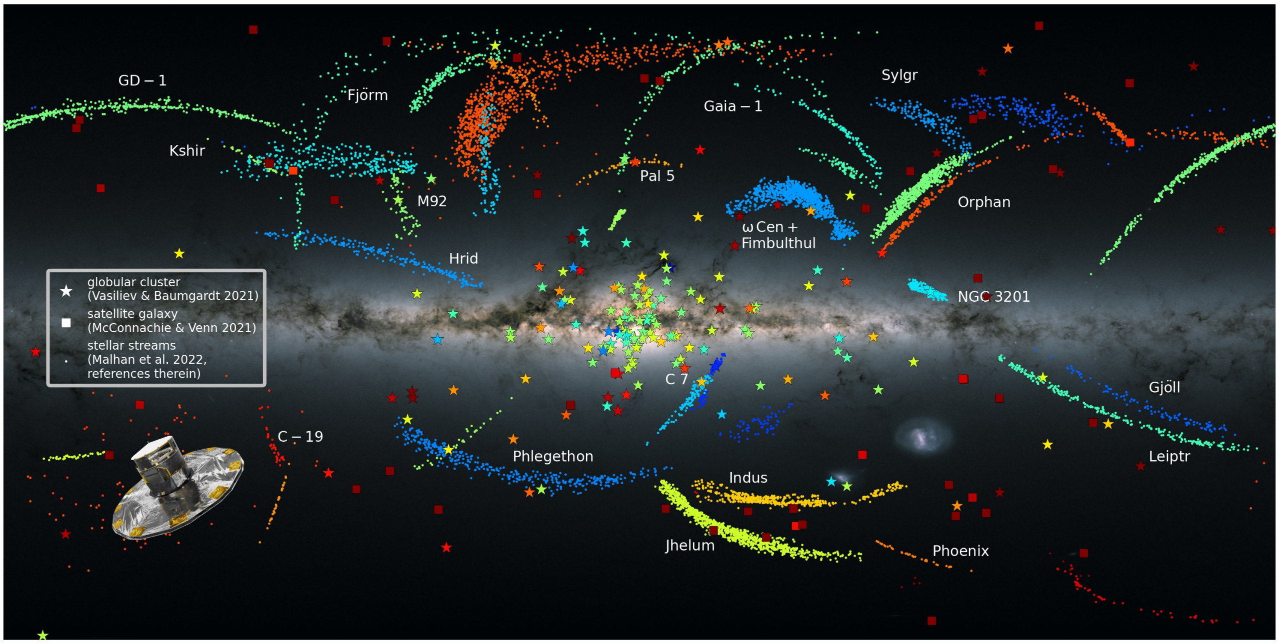

Figure 4: *The Milky Way galaxy and its stellar streams (colored dots), globular clusters (star symbols) and dwarf galaxies (small squares). Of all the known streams,* 46 *of them detected by applying the* `STREAMFINDER` *algorithm to the Gaia dataset are shown. The color corresponds to distance, with "blue" objects being closer to us and "red" objects being farther out in the halo. Figure adapted from results presented in Malhan et al. 2018, MNRAS, 477, 4063 & Ibata et al. 2021, ApJ, 914, 123.*

analysis of satellites and streams can therefore provide measurements of the Galactic (DM) potential.

Stellar archaeology uses chemical and kinematic properties of stars as diagnostic tools to understand the history of a galaxy and also infer the nature of the first stars. The first stars are anticipated to have zero metallicity, but no such stars have been observed in the Galaxy to date. It is suggested that due to their massive nature, the first stars exploded as supernovae early on, and created the first metals in the Universe which aided cooling of the gas and formation of the first low mass stars. Hence, the detection and study of stars with extremely low metallicity is of great importance. One of the most useful probes for chemical-tagging of stars is the presence of heavy elements in low mass stars ($< 1M_\odot$), as such stars do not synthesis or destroy them during their evolution, indicating their birth in an enriched environment. The elements, beyond iron, are synthesised by slow and rapid neutron capture processes, known as s-process and r-process, respectively. It is expected that half of all the heavy elements are produced through r-process, with some of the major contributors of the r-process enrichment in the galaxy being binary neutron star mergers, neutrino-driven winds in Type-II supernovae, prompt explosion of low-mass supernovae and collapsars.

Resolving and probing the stellar populations in nearby galaxies can help address the astrophysics of stellar evolution, formation of different structural components of galaxies, the role of accretion in galactic formation, the nature and distribution of DM and the earliest epochs of galaxy formation and reionization. The Large and Small Magellanic Clouds (MCs) are the largest, gas-rich, metal poor and the most massive interacting satellites of the Milky Way. The MCs span a large area in the sky and have been the target of many dedicated optical and near infrared surveys that provide a detailed three dimensional structure, as well as star and cluster formation history of these galaxies. Our neighbour, the Andromeda Galaxy (M31), is comparable to or possibly larger than the Milky Way by mass, and is tidally interacting with its largest satellite M33 with a bridge of gas connecting them. Although it is a spiral galaxy like the Milky Way, there are structural differences in terms of chemical abundance gradients in the disks suggesting a major merger in the recent past (~ 2.5 to 4.5 Gyr) with a gas-rich satellite galaxy. This scenario provides an invaluable case study of how major mergers can affect star formation, galaxy structure, and disk survival. In addition to these large galaxies, there has been an active interest in investigating the smaller and fainter dwarf galaxies in the local neighbourhood of the Milky Way in order to understand how the phenomena such as reionization in early Universe affected the evolution of these galaxies, and their star-formation histories.

Key Science Questions

What phenomena are responsible for chemical anomalies in stellar photopheres of varying masses? Why is there a difference between the chemical abundance of Solar photosphere and helioseismology predictions? What parameters and their interplay are responsible for the location of a star as it evolves on an HR diagram? What are the pathways by which binary/multiple-star systems evolve? What would have been the chemical composition of the first stars? How did they evolve? How do we explain the synthesis of heavy elements (beyond iron) observed in the Universe?

How can we accurately predict the disk potential of the Milky Way? What are the ways in which the multi-component Milky Way disk responds to passing satellites? How have galaxies assembled their current stellar sub-structures, and what is the role of dark matter therein? Can Milky Way stellar streams provide the answer to the dark matter distribution vis-a-vis alternate gravity theories? What is the role of accretion in galaxy formation and evolution? What is the nature of interaction between the Magellanic clouds themselves and the Milky Way? What is the effect of galactic mergers on star formation, galaxy structure, and disk survival in large spiral galaxies? Can we infer the merger histories of our neighbour galaxies Andromeda (M31) and Triangulam (M33)? What is the impact of re-ionization on low mass dwarf galaxies?

Recommendations

It is recommended that a strong interaction and collaboration between theorists, observers and numerical simulators be developed to engage in more realistic problems in the studies of galaxies. Theoretical modelling to understand the late stages of stellar evolution and binary evolution are need to enhance the present, largely observations driven, scale of stellar astronomy in the country. Predictions from different nucleosynthesis models and the uncertainties from nuclear physics cannot be neglected. High performance computing facilities are required for simulations as well as for the handling analysis and databases of large datasets. Listed below are the recommendations for near to long term observing facilities.

Near-term ($\sim$ 5 years): i) Access to existing 8-10m class telescopes with deep imaging and integral field spectroscopic instruments with resolving power $R \sim 2000$ to resolve stellar populations in the Local Group, (ii) participation in large spectroscopic surveys such as the 4-metre Multi-Object Spectroscopic Telescope (4MOST) or the Dark Energy Spectroscopic Instrument (DESI), (iii) high resolution spectrograph and Integral Field Spectrograph (IFS) on the 3.6m Devastal optical telescope (DOT), ARIES, Nanital, (iv) Computing facilities to run simulations for Milky Way as a reference galaxy from the predictions of cosmological simulations (e.g., Aquarius, Illustris, TNG, Eagle).

Mid- to long-term ($10- > 15$ years): (i) a space mission with $1-1.5$m aperture to observe stars closely along different lines-of-sight in the Milky Way with provision for asteroseismology, (ii) UV scanning spectrograph with $R \sim 10000 - 20000$ for the proposed UV mission INSIST, (iii) A National large 10-12m class optical telescope with high resolution, high blue throughput and near-infrared spectrographs, and AO enabled high spatial resolution in the NIR (iv) participation in large spectroscopic facilities such as Maunakea Spectroscopic Explorer, (v) spectroscopic array of telescopes.

1.6 Galaxies, Clusters of Galaxies and Inter-Galactic Medium

The formation and evolution of galaxies, their aggregation to form groups and clusters while interacting with the diffuse medium in the space between them are phenomena of fundamental interest for astronomers to probe the cosmic history and to understand the current state of the Universe. Over the last three decades, the availability of several cutting-edge space- and groundbased telescopes around the world has transformed our views on how galaxies form and evolve over cosmic time. Although the exact nature of the dark components of the universe, which dominate the energy budget, is not well understood, cosmological hydrodynamical simulations are remarkably successful in reproducing the large-scale properties of the universe and, to a large extent, galactic-scale phenomena. Galaxy evolution, in a nutshell, is the redistribution of cosmic baryons in space and in phase, and understanding galaxy evolution involves processes with a wide range in density, temperature, and length scale. Therefore, a multi-wavelength approach is essential. The astronomical scales involved range from that of kiloparsecs (galaxies) to several megaparsecs (intergalactic medium (IGM); Fig. 5). Galaxies, groups, and clusters are embedded in the densest parts of the large-scale cosmic filaments. The volume filling empty regions, i.e., the IGM, harbours most of the cosmic baryons at all epochs.

Multiwavelength observations together with theoretical modelling and simulations, that include contributions by Indian astronomers, have led to some significant new understanding in the recent times. For example, galaxy dynamical models, including gas in addition to stars and dark matter, have led to an understanding of the ubiquity of spiral features in galaxies and the role of the thickness of the galactic disk in setting up the pattern speed, which in turn drives the dynamical evolution. The diffuse medium surrounding the galaxies, the circumgalactic medium (CGM), that is of crucial importance to understand galaxy evolution has been found to be anisotropic, inhomogenous, and multiphase. Galaxies grow by the accretion of mass, and major changes can happen when galaxies merge. Studies have found enhancement or suppression in star formation, changes in galaxy morphology, star bursts, and the triggering of jets from supermassive blackholes in active galactic nuclei (AGN). Dual and triple AGN have been discovered and studied using multi-frequency observations. On the megaparsec scale, the presence of magnetic fields and cosmic rays (including relativistic electrons) has been known to be ubiquitous in clusters. Large surveys in radio bands have led to a statistical understanding of the occurrence of diffuse radio sources in clusters known as radio halos and relics. Multi-band studies

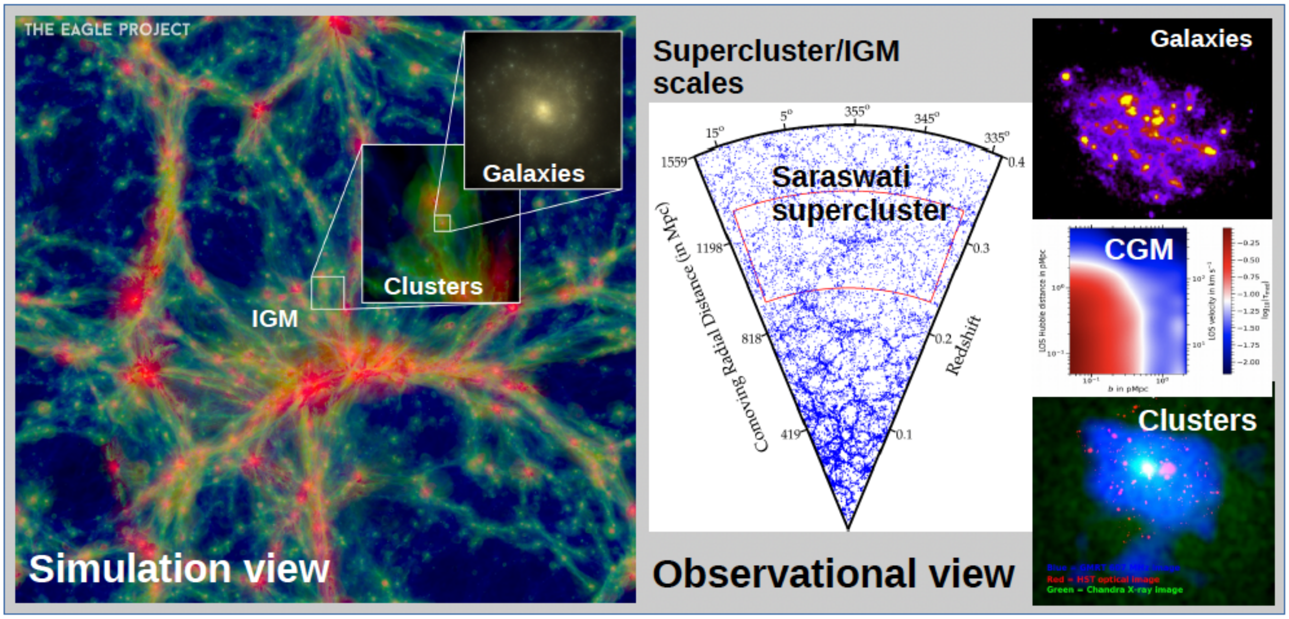

Figure 5: *Simulation (left) and observation (right) views of the galaxies, clusters and IGM scales.* **Left:** *The large-scale gas distribution (100 cMPc x 100 cMpc) in the EAGLE cosmological hydrodynamical simulation in a thick slice (20cMpc) through the $z = 0$ universe. The intensity represents the gas density, while the colours represent the gas temperature (blue: $T < 10^{4.5}$ K, green: $T = 10^{4.5-5.5}$ K, red: $T > 10^{5.5}$ K). The first zoom (10 CMpc on a side) shows the gas, whereas the last zoom (60 ckpc on a side) shows the extinction corrected stellar light.* **Right:** *Observational views of the various scales. Middle right panel shows the distribution of galaxies in the Sloan Digitized Sky Survey that form the Saraswati supercluster. The top right panel shows NUV image with the AstroSat-UVIT. The right centre panel shows the Ly-alpha optical depth distribution around low redshift galaxies as a function of transverse and line of sight distances and the right bottom panel shows the GMRT radio emission in blue with X-ray and optical emission in green and red respectively. Images adapted from Schaye et al MNRAS, 2015, 446, 521; Bagchi et al 2017, ApJ, 844, 25; Das et al 2021, JApA, 42, 85; Dutta et al. 2023, arXiv:2303.16933; Kale et al 2019, MNRAS, 486, 80.*

comparing radio, X-ray, and optical studies have led to the modelling of the dynamics of cluster mergers and constraining the acceleration of charged particles via turbulence and shocks in the ICM. The outskirts of clusters are less explored observationally due to the lack of sensitive probes needed to study these regions of very low density. The first-ever statistical detection of cool metal-rich gas at cluster outskirts was reported by Indian astronomers using stacked absorption line spectra. This detection implied that the metal-rich gas at the cluster outskirts arises from stripping rather than from the gas in the CGM of cluster galaxies. The discovery of superclusters of galaxies, such as the 'Saraswati' supercluster, has revealed that some extreme large-scale prominent matter density enhancements were formed in the universe very early on, at the epoch when dark energy had just started to dominate.

Key Science Questions

The major outstanding questions in the field of galaxies, clusters, and IGM are: What drives the behaviour of star formation across the history of the universe? How do galaxies transform from blue star-forming disk galaxies to red and dead ellipticals? How does the galaxy's mass influence the efficiency of star formation? How do galaxies drive large-scale outflows? Where are the cosmic and halo 'missing' baryons and 'missing' metals? What are the cooling and heating processes in the diffuse media, from galactic scales to large-scale structures? What is the nature of the magnetic field inside and beyond galaxies? What are the properties of turbulence on these scales? How do charged particles in diffuse media accelerate? Do fundamental constants vary across cosmic time and space?

Recommendations

Indian astronomers have made significant contributions to answering some of these outstanding questions over the past several decades, despite limited resources, with the Giant Meter-Wave Radio Telescope (GMRT) being the only in-house cutting-edge observatory. All the existing ground-based observatories in India are deemed unsuitable for state-of-the-art galaxy evolution studies, particularly for distant galaxies. Joining the Thirty-Meter Telescope (TMT) collaboration has been a major milestone for Indian astronomy. In order to keep up with this rapidly evolving field, a few recommendations are provided.

The Indian astronomical community must build an 8–10 meter-class optical/near-IR telescope with capabilities similar to ESO/VLT and/or Keck.

A near-term development would be to augment the instruments on the 3.6-m Devasthal Optical Telescope (DOT) to include adaptive optics (AO), multi-object spectroscopy (MOS), and integral field spectroscopy (IFS).

To stay competitive with the world in radio bands, we must invest in the improvement of the existing GMRT observatory, for example, by supporting the planned Expanded-GMRT (E-GMRT). Participation in SKA is also highly preferable to secure access to the multiple radio bands enabling science from low to high frequencies. Investment in improving the available software to analyse the radio band data and the access to computing power is also an important aspect of supporting the science.

For immediate access to the state-of-the-art, multi-wavelength observing facilities, it is recommended that Indian astronomical community must acquire access to larger international observing facilities/telescopes by joining international consortia.

With the lessons learned from the success story of AstroSat, it is important to plan for future space missions, and to utilize the window of opportunities in space to make unique and leading contributions, particularly when there is no servicing mission planned for the Hubble Space Telescope (HST).

Theoretical studies of galaxy evolution have become dependent on hydrodynamic simulations. Additionally, probing the statistical properties of supernovae driven turbulence and the effects of multi-phase structure of the ISM on magnetic fields and vice versa requires high resolution magneto-hydrodynamic (MHD) simulations. These simulations require extensive computational resources, which are often not easily available in India. Getting access to such large computational resources in the future is essential for obtaining a meaningful comparison between theory and observations.

Astronomy research is not only limited to scientists but can be extended to young students and citizens via citizen science projects. Through the citizen science collaboratory ‘RAD@home’, thousands of university students and citizens have helped analyse the three-colour optical and radio astronomical images to make interesting discoveries leading to impactful scientific work. Such programmes will be successful in introducing young citizens to astronomy and attracting more students to do scientific research.

1.7 Supermassive Black Holes and Active Galactic Nuclei

Super Massive Black Holes (SMBHs) are hosted by almost all galaxies at their centres. They play a crucial role in powering the extraordinary luminosity of active galaxies, as well as in the evolution of galaxies. Accretion of matter onto central SMBHs in active galaxies lights the closest environments and illuminates the surrounding regions, thus allowing to probe a vast range of physical phenomena including those under the influence of strong gravity near the event horizon to those at the Galactic scale and beyond. Active galactic nuclei (AGNs) are the most luminous non-explosive cosmic sources that provide unique observational signatures over all electromagnetic bands. Most of the energy generated in the accretion process is released within a few tens of gravitational radii of the central SMBH, and is emitted in the form of X-ray and Ultra-Violet (UV) radiation. Both the matter and the emission from the immediate vicinity of the SMBH are strongly affected by General and Special Relativity. The inner regions are also thought to be responsible for launching winds, outflows and relativistic jets that play an important role in the feedback processes at larger scales and affect galaxy evolution. Drastic changes in the physical conditions and/or geometry of the innermost regions leads to some of the transient phenomena such as those observed in changing-look AGN, tidal disruption events, and quasi-periodic eruptions. Thus, a detailed understanding of the regions in the immediate vicinity of SMBHs is crucial to understand the physics of the most efficient energy generation processes, general and special relativistic effects, accretion/ejection mechanisms and transient phenomena.

Jets serve as ideal laboratories for investigating the innermost regions of AGNs to study their composition, dominant radiation, particle acceleration processes, and jet-launching mechanisms. The driving mechanism for relativistic jets in AGNs is believed to be the interaction of the central black hole's accretion disk with its magnetic field. The observed non-thermal emission from AGN originates in close proximity to the central engine. It is believed that ultra-relativistic particles accelerated by shock waves travelling down the jet produce the emission. This process transfers the plasma's bulk kinetic energy into the random motion of particles, leading to cooling via non-thermal mechanisms, which results in observable radiation. However, recent findings of rapid variability in high-energies and polarised emission challenge this current paradigm and suggest that the particle may be accelerated through turbulence or magnetic reconnection within the jet. Detailed observations capable of constraining the precise mechanisms of jet formation and distinguishing between different theoretical models are challenging. High cadence, multi-wavelength, tempo-spectral information is needed to shed light on jet physics and its launching mechanisms. Therefore, it is imperative to conduct time-resolved observations of emission variability and polarisation information and utilise high-resolution techniques such as sub-parsec scale mm/radio imaging to develop a comprehensive understanding of the jet formation process and its correlation with the accretion disc. These observations will provide data that can be compared with theoretical models and simulations, such as General Relativistic Magnetohydrodynamics (GRMHD) simulations.

The discovery of high redshift ($z > 6$) quasars, have shown that SMBHs of masses $M_{BH} \sim 10^9 M_\odot$ existed within the first billion years after the Big Bang. The processes responsible for the initial formation and growth of the "seed" SMBHs remain unknown. Understanding this aspect requires the deepest surveys and follow-up observations in different bands to identify the first SMBHs.

The hierarchical models of galaxy formation and evolution imply formation of massive black hole binary systems. These massive binary black holes will eventually spiral in and merge to form a single SMBH of the new galaxy. The study of SMBH binaries has important implications for studying the end stages of galaxy mergers and the growth of galaxies as well as their central SMBHs. The Laser Interferometer Space Antenna (LISA), being planned by ESA, will open the door to the next major observational breakthrough of coincident detection of gravitational and electromagnetic wave signatures associated with merging massive black holes including SMBHs of masses up to $10^7 M_\odot$. These detections will lead to a new era of multi-messenger astrophysics that will probe growth and evolution of massive black holes and their connection with galaxy evolution.

AGN driven outflows can transport energy and momentum to gas both within the host galaxy and its neighbouring environment. Such interactions can impact the star formation rate (SFR) of the host galaxy, both by boosting the local SFR at the sites of compression (positive feedback) and reducing SFR at shocked regions with turbulence (negative feedback) and also by removal of gas from the galaxy. The exact mechanism responsible for the origin of the winds/outflows has been a long standing problem. While the low ionisation UV winds may be launched by the strong radiation pressure of the central disk/corona, the origin of the highly ionised X-ray winds is still unclear. Probing the relative importance of winds/outflows and jets in carrying the kinetic power, the connection between them and the accretion state (such as low/high Eddington ratio, radio-loudness, etc.) will help understand accretion/ejection mechanisms in AGN, and the impact of AGN winds on galaxy evolution.

Key Questions

How did the first SMBH or the seeds form? How do the seeds of SMBHs grow initially? What are the effects of strong gravity and measurement of black hole spin?

Is the accretion disk standard as predicted by theory? Does the disk extend down to the last stable orbit or it is truncated? What is the geometry of the corona? Is the corona purely thermal or partly non-thermal? How is the corona powered? What is the connection between the disk, corona, and the jet? Is the corona really the base of the jet? What are the jet ejection mechanisms? What is the physics of the most efficient energy generation process and the accretion flow?

What drives the AGN outflows? What is the duty cycle of the outflows - are they stochastic intermittent phenomenon or do they occur more frequently? How is the stellar mass assembly affected by jets and AGN driven winds?

Recommendations

The study of SMBH and the AGN phenomenon require multi-messenger, multi-wavelength observations as well as theoretical models and simulations involving relativistic astrophysical processes. The AGN community in India has grown, with the capability to handle data from low energy radio to high energy gamma-rays. This has created the demand for more observational facilities. In parallel the availability of enormous amount of archival data spanning across wavelengths has also lead to the growth of the AGN community in India. The availability of such huge data set in the public domain currently and with the possibility of more data getting flooded from mega ground and space based projects, there is a requirement of more number of professional astronomers. Provided below are some recommendations that will enable Indian astronomers to continue being in the forefront in the field.

AGN researchers in India have largely made individual efforts. It is now time to develop collaborative framework for researchers in India to build a synergy between observers and theoreticians in different sub-areas. The collaborations must utilise existing facilities in an effective way, organise training programmes and participate in the development of upcoming telescopes relevant for AGN research.

Policies leading to a national consortium of telescopes providing joint observing opportunities need to be evolved as these will provide means for efficient use of the facilities and observational programmes.

The era of Vera Rubin Observatory will create a new demand for large scale spectroscopy. To enable follow-up of AGN activity, and new AGNs detected by the LSST, it is important to develop multi-object spectroscopic capability as well as integral field unit (IFU) spectroscopic capability on the existing 2-4m class telescope in the country.

Polarimetry is a relatively unexplored area and hence has great potential to grow in the Indian context. This is also an area where moderate aperture telescopes can perform better compared to large aperture telescopes. The requirement in the short term is to have a good imaging/photo-polarimeter on some of the existing telescopes. In addition, future telescopes should be equipped with polarimetric capability.

India has several moderate aperture telescopes that are in operation. Efforts must be made to network these telescopes so that national/multi-institutional programs could be executed to increase our understanding on AGN science. This might require modernization of existing facilities such that they are semi-automatic. One such facility of this kind in India is the 0.7m GROWTH-India telescope. Few such telescopes (albeit with a larger aperture) need to be established in several parts of India, possibly operated under a central single commanding facility. Though, this could be thought of as a mid-term plan, a similar thing in the near term that could be executed is the networking of the telescopes that will become operational in the coming couple of years.

The Indian community is handicapped in getting access to data from large aperture telescopes. The situation is not expected to change in the future when telescopes such as GMT, TMT and ELT comes online, irrespective of India getting privileged access to TMT via its share in the TMT project. Therefore, to carry out individual scientists driven science projects, there is an urgent need to have (a) an Indian 10-12 m class optical-infrared telescope and (b) immediate guaranteed access to large aperture telescopes outside India via inter-institutional and/or inter-national agreements.

AstroSat, with its UV/X-ray capability, has generated new researchers and expertise. This needs to be taken forward by a follow-up mission with enhanced UV/X-ray sensitivity and capability. Space missions with X-ray polarisation capability must be taken forward. The expertise gained in UVIT needs to be taken forward with enhancement in (a) light gathering power, which demands 1-2 m aperture, (b) imaging as well as spectroscopic capability.

1.8 Compact Objects

In increasing order of compactness and gravity, white dwarfs (WDs), neutron stars (NSs), and black holes (BHs) are laboratories for understanding the behaviour of matter and light under the strongest magnetic and gravitational fields. The study of compact objects (CO) thus spans multiple areas of physics and astronomy: nuclear physics, general relativity, magnetohydrodynamics (MHD), electromagnetism, thermodynamics among many others. Broadly, the field studies the imprints of relativistic gravity, magnetic fields, plasma movement, and nuclear physics on observations. Observational constraints are derived from traditional optical/X-ray/γ-ray astronomy and increasingly from neutrino and gravitational wave (GW) observations. Each of these aspects invokes cutting-edge theoretical, experimental, and observational methods. The study of compact objects has good synergy with the studies of transients, evolution of galaxies, stellar structure and evolution.

Sirius B was first discovered in 1863 by Alvan Clark and identified later as a WD is the first of the CO to be discovered. WD in binaries should be the simplest case of evolution of compact binaries and yet there are discrepancies in the current population models and the properties of the observed samples. Theoretically we are still unable to account for the observed characteristics of the known populations of WDs in both interacting and detached binaries. Accreting WDs, such as those in cataclysmic variables (CVs) are particularly interesting as these systems can lead to the formation of either neutron stars or thermonuclear explosions. Among the most important aspects of compact binary evolution are the multiple pathways leading to thermonuclear explosions such as the type Ia Supernova (SN Ia), calcium-rich transients, etc. While WDs are supported by electron degenracy pressure, NSs are supported by neutron degeneracy pressure ans well as nuclear strong interactions. Although the general idea about NS is known for more than half a century yet its internal structure namely the equation of state (EoS) is not. The standard approach is to constrain theoretical models via observations. Observations of various stellar structural properties of neutron stars can provide us a promising direction to understand these states of matter. Recent observations of binary neutron star merger GW170817 event has strongly constrained a number of stiff EoS. A sub-sample of neutron stars emits beams of electromagnetic radiation that make them detectable as pulsars. Their spin period is very stable and so the pulses detected as they spin are like ‘celestial clocks’. Stable millisecond pulsars have been used to detect nano-Hz gravitational waves the International Pulsar Timing Array collaboration of which the Indian Pulsar Timing Array consortium is a member. The presently known population of about 3400 pulsars is less than 5% of the predicted number of detectable radio pulsars, indicating a lot more are there to be found. Recent survey using the Giant Meter wave Radio Telescope (GMRT) has resulted in the discovery of several pulsars including millisecond pulsars, very wide profile pulsars and pulsars with gamma-ray counterparts.

The basic idea that centres of galaxies harbour central massive BH, and the act of feeding on matter, gas dust, stars of the galaxies which happen to venture within the accretion radius, makes the centres of some galaxies to be 'active' is now well understood. In addition, in many of the X-ray binaries, the primary object was identified as a BH, and these objects were called microquasars (mini-quasar), as the feeding and ejection behaviour resembled the quasars over a smaller scale. Over the last few decades a lot of progress has been made, both in the theoretical and observational front. It has been established that there are broadly two accretion modes: one the Keplerian disc, which is the source of optically thick modified black body type thermal emission, while the other, a non Keplerian component, which is the source of power-law emission. Significant progress has been made in the theoretical understanding of the physics of the accretion and ejection behaviour of matter around BH. Through modelling, computing spectrum from these models and then fitting with observations we broadly know that there is a component which is rotating very fast and producing the thermal spectrum, while another component, which is advecting faster, produces the power-law emission.

Key Science Questions

The ingenious Event Horizon Telescope (EHT) campaign has enabled imaging the shadow of the BH of M87 and our own galaxy. In addition the LIGO observatory has established that stellar mass binary BHs can merge to form intermediate mass BHs. The upcoming facilities such as LIGO-India, Einstein Telescope, Cosmic Explorer, DECIGO, LISA and other multi-messenger facilities will make it possible to get crucial inputs to our understanding of several key aspects in fundamental nuclear interactions in determining NS internal structure and other various unexplored physics of the matter under extreme conditions, which have been a subject of mostly theoretical speculations to date. Additionally, space missions, such as the XPOSAT, that will have the unique feature of measuring X-ray polarization as well as spectroscopy, will open hitherto not frequented territory of quantitative estimation of geometry and physics of X-ray emitting region, magnetic field structure etc. All of this together with advances in theory and simulations will enable addressing several key problems. What are the various binary evolution channels that lead to the formation of binary systems with compact objects, and their effect on the progenitor populations of supernovae, GW events, etc? What is the role of magnetic field in the evolution, radiation and behaviour of compact objects? What is the equation of state of the dense matter in neutron stars? What the effects of spin and accretion processes on jets and jet launching, particularly in the case of black holes? What is the nature of the QPOs and is there a relation between jets and QPOs? A better understanding of the radiation processes in compact objects, particularly from accretion discs and jets.

Recommendations

Foster collaboration between theoretical and observational astronomers.

Observing facilities for search and follow-up of pulsars such as the eGMRT, X-ray satellite with polarimetric capability.

Computational facilities: A new rapidly changing aspect of computation are advanced accelerators. Apart from graphics processing units (GPUs), field programmable gate arrays (FPGAs), tensor processing units (TPUs), neuromorphic computing units are now being integrated into computing nodes to form heterogeneous clusters.

Strengthening and accelerating sustained community development through schools and workshops and citizen science projects.

1.9 Time Domain Astrophysics

Time domain astrophysics (TDA) is at the forefront of global astronomical research. A major thrust area in this decade is multi-messenger astronomy, spurred by long-awaited groundbreaking discoveries such as the detection of electromagnetic radiation and gravitational waves from merging neutron stars (GW170817), the detection of neutrinos from a flaring blazar (TXS 0506+056 / IceCube-170922A), or the detection of high energy TeV $\gamma-$rays from a recurrent nova outburst (RS Oph). Advancements in technology have enabled astronomical surveys to probe wider parts of the sky, at higher sensitivities, and faster cadences. This has uncovered new classes of rare, faint, and fast transients that were missed by older surveys. Key among these are the fast radio bursts: a phenomenon so enigmatic that we still have only a rather vague understanding of what they might actually be. Similarly, tidal disruption events that were rather rarely seen a decade ago are now routinely discovered, with occasional surprises like the launch of relativistic jets. Such discoveries of rare, extreme events are all set to grow in the near future with upcoming observatories like the Vera Rubin Observatory, Nancy Grace Roman space telescope, Square Kilometre Array, etc.

The flurry of activity in new transients is accompanied by remarkable progress in understanding well-known classes like novae and supernovae. Early observations have caught shock breakouts in several supernovae, and the high sensitivity and regular monitoring have been used to further our understanding of their progenitors, evolution, and circumstellar environments. The same holds true for novae: recent observations have given great insights into shock physics, radiative processes, particle acceleration, and mass accretion in binary systems. All these studies are propelled by the ability to undertake coordinated multi-wavelength observations.

Transients are valuable astrophysical laboratories, offering “real time” studies of various astrophysical phenomenon. They form a unique probe into non-equilibrium dynamic processes, and some of the most extreme environments in the universe. In turn, understanding transients requires a confluence of many aspects of fundamental physics: such as accretion, shock and particle acceleration in relativistic media, radiation mechanisms, etc – in turn drawing upon general relativity, magnetohydrodynamics, and even quantum electrodynamics. Explosive transients are also likely candidates for production of ultra-high energy cosmic rays and neutrinos. They are important sources of most of the elements in

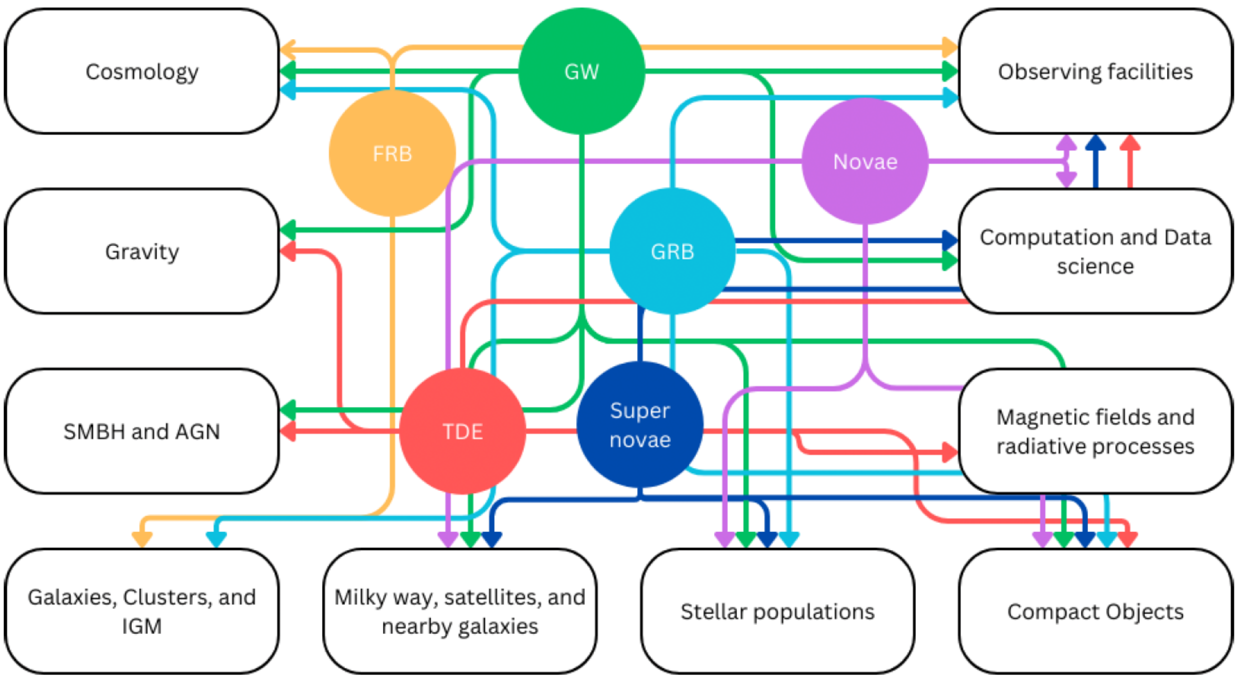

Figure 6: *Synergy between major classes of transients and other areas of astronomy and astrophysics.*

the Universe, lead to the chemical enrichment, and regulate star formation of galaxies. Study of electromagnetic counterparts to GW sources will help us understand the sites of r-process nucleosynthesis and probe the nuclear equation of state. In short, study of transients has synergy with several other areas of astronomy as shown in Figure 6.

Key Science Questions

The study of a large number of transients, and discovery of new types and classes have led to probing the progenitors of may transients. This has, however, also led to several open questions. Do thermonuclear supernovae arise from single- or double-degenerate channels? What kind of high energy thermonuclear explosions are novae progenitors of? What variation in progenitor properties creates the diversity in core collapse supernovae, and why? Why do only some core collapse explosions launch jets, creating long gamma ray bursts (GRBs)? Do all short GRBs arise from binary neutron star mergers, or can some arise from neutron star - black hole mergers as well? Lastly, we are just scratching the surface for some classes of transients: for instance, what are the progenitors of Fast Radio Bursts (FRBs), and are they a single population?

Another area of interest is the interaction of these sources with the environment, and the possibilities of using them to probe the environment. How do novae impact the chemical enrichment of the galaxy? How are the outer layers of massive stars stripped in their final evolutionary stages, and how does the subsequent supernova explosion alter the environment? When and where in the history of the cosmos did stars form and die, and does this change over time? Can we use distant GRBs and FRBs as probes of high redshift host properties, intergalactic medium, and intergalactic magnetic fields?

Lastly, we come to open questions exploring the broad phase space of transients themselves. What are the rates and energetics of tidal disruption events, and what creates relativistic jets in some of them? What source types lay hidden in the FRB zoo? What transient populations occupy the low luminosity regions of high-energy bands? How do novae properties relate to the source stellar populations?

Recommendations

Time domain astronomy being a vast, rich field with synergies across most other fields in astrophysics, it is hard to narrow down to a few thrust areas. However, leveraging on our longitudinal advantage, existing and future facilities, we define a few areas that would be scientifically most promising for the community. (i) Study of supernovae with regular photometric monitoring and sparse spectroscopy to identify the physics-wise most interesting events for further follow-up, (ii) understanding the high energy radiation from novae, and hence the energetics of the explosion, studies of novae in low-radio frequencies, (iii) fast transients. The study of fast transients - be it afterglows of GRBs, new classes like FBOTs or just the early-time studies of novae and supernovae - requires a global network of telescopes. There are few other telescopes at Indian longitudes, and this gives us a unique opportunity to obtain high-quality data that most other observers around the world cannot get. Focusing on these can be a strong differentiating factor for the Indian community. The coming decade will see a large number of cosmological bursts with FRBs discovered by CHIME, SKA etc, along with faint GRBs found by SVOM, Daksha etc. This opens up new possibilities in using these as probes for intergalactic medium, intergalactic magnetic fields, etc. There is a growing Indian community in numerical simulations that can contribute heavily to time domain astrophysics - be it modelling of GRB jets, kilonovae, explosion physics, modelling the light curves and spectral evolution, etc.

We provide below a few recommendations regarding facilities and their operations to facilitate and enhance time domain astronomy.

Augmentation of the existing ground based facilities with a National Large Optical-IR (10m class) telescope.

An array of small (m-class) telescopes for monitoring of transient sources. Such a network of telescopes will be complementary to LIGO in efforts to find EM counterparts of GW sources as they can help cover wide, deep, fast, and hedge against weather.

Identify niche areas where the outcomes will be the defining standards for further research, such as polarimetric studies. An excellent current example is Xposat, which will be the sole global asset for soft x-ray polarisation studies. More emphasis can be given in the development of polarimetric imagers and spectrographs across all bands, which can allow us to probe jet physics, nova physics, FRB emissions, etc.

UV and X-ray telescopes, such as the proposed space missions, INSIST and Daksha.

Continuing our participation in the next-generation international mega projects, such as those in the Vera Rubin Observatory, Thirty-Metre Telescope, Square Kilometre Array, and LIGO-India, is essential for future time domain studies.

A major limitation to current studies are target of opportunity observations. We recommend that steps be taken immediately to (a) have uniform and well-defined policies for ToOs across telescopes and wavebands: both ground- and space-based, (b) typical ToO times are far too short given the increasing size of the community, scientific outcomes delivered by the field, etc. The cap on ToO times needs to be drastically increased, and individual proposals should be awarded ToO time based on scientific merits, (c) observatories develop and implement policies that make it possible for every astronomer in the country to have equal abilities to trigger ToOs without needing a collaborator on-site, and (d) the entire ToO procedure including proposal preparation, submission, evaluation, observation, and getting data in hand be sped up through revision of policies, sensitisation of evaluators and observers, and strict adherence to policies defined above. Both ground-based and space facilities should implement mechanisms for “disruptive” ToO observations within hours for high-value targets.

1.10 Strong Gravity Physics

The first detection of gravitational waves (GWs) in 2015, followed by subsequent observations of GWs from dozens of compact binary mergers involving stellar-mass black holes (BHs) and neutron stars (NSs) have firmly established GW astronomy. The upcoming LIGO-India detector will add to the existing detectors enhancing the sensitivity for detection, and localisation of GW events. The next generation ground-based detectors (such as Cosmic Explorer and Einstein Telescope) that will observe in the audio frequency band (few Hz – few kHz), will detect mergers of NSs and stellar- and intermediate-mass BHs out to cosmological distances. These detectors will elevate GW observations to a novel and precise astrophysical tool in the next 15 years. The Indian GW community is actively involved in international GW collaborations, in theory, experiment and data analysis. Complementing the GW detectors (LIGO, VIRGO, KAGRA), maturing pulsar timing arrays (PTAs) have recently obtained strong evidence for nHz GW background, likely due to merging supermassive black hole (SMBH) binaries, ushering the era of nHz GW astronomy. The Indian PTA (InPTA), an IPTA constituent, that employs the uGMRT is providing critical observational data, analysis algorithms, and theoretical constructs towards this effort. The future, space based mHz GW detector, the Laser Interferometer Space Antenna (LISA), is expected to be launched by the middle of the next decade. Likewise, missions that will search for imprints of very low-frequency GWs in the polarisation of the Cosmic Microwave Background (CMB), including the India-based CMB-Bharat project, are also being explored actively. There are interesting proposals to build deci-Hz GW detectors in space or on the moon that will bridge the gap between mHz LISA and ground-based detectors. Some of these projects would be closely aligned with the Indian Space Program. The science case for such deci-Hz detectors is already being pursued by the community.

Various other astronomical observations are also probing gravity in its strong-field regime. Observation of stellar orbits at the centre of our galaxy using infrared telescopes has given us conclusive evidence for a supermassive compact object at the galactic centre. High-resolution radio imaging of the central compact objects in our galaxy as well as M87 by Event Horizon Telescope (EHT) provided us with the first horizon-scale image of the compact object and its accretion disc. Though these supermassive compact objects are consistent with being BHs in general relativity (GR), more detailed observations are required to confirm this with a high level of precision. Next-generation experiments such as ngEHT should be capable of achieving high-resolution images of BH event horizon and of probing nHz GW emitting SMBH binary candidates like OJ 287.

Inferring the equation of state (EOS) of NSs is also an important topic in gravitational physics which has implications for astrophysics and nuclear physics. Recent X-ray observations using the Neutron Star Interior Composition Explorer (NICER) mission have provided important constraints on the NS EoS through NS radius measurements. GW observations of the binary NS (BNS) merger GW170817 have already provided us with an opportunity to measure the mass and tidal deformation of NSs directly, providing another avenue to constrain the NS EoS. Future GW/multi-messenger observations of BNSs will tightly constrain the NS EOS.

Theoretical work in gravitational physics, analytical and numerical, has a crucial role to play in all of these observational frontiers. There is a large community in India that is involved in the theoretical modelling of GWs, BH accretion, etc, both within GR and in modified theories of gravity. Indian contributions to theoretical gravitational physics have been outstanding.

Key Science Questions

The upcoming GW observations have the potential to discover new GW sources and phenomenon. This will enable addressing some of the key aspects such as how do binary BHs (BnBH) form and evolve? How do SMBH's form and evolve? What is the demography of BnBHs and SMBHs? What is the structure of ultrarelativistic jets? The other key questions of interest in this area are the state of extremely dense matter and structure of NSs and testing GR in the relativistic strong field regime. What is the nature of dark matter and dark energy - can this be addressed by alternate theories of gravity? Do cosmic strings exist? Are there other exotic phenomenon such as domain walls, extra space-time dimensions, etc?

Recommendations

LIGO-India is a golden opportunity for the Indian physics and astronomy community to be a major player in a rapidly growing frontier. Dedicated efforts should be made towards the construction, commissioning and timely operation of LIGO-India to maximise its impact on the worldwide network of GW detectors.

Even as LIGO-India is under construction, there should be an involvement in high-frequency GW observations using ground based interferometric detectors through continued active participation in the LIGO-Virgo-KAGRA collaboration.

Nano-Hz GW observations using PTAs. The InPTA consortium will continue to establish efforts towards multi-messenger nHzGW astronomy during the SKA era. Upgrading of current facilities to fulfil PTA science potential during the SKA era should be encouraged. This can, for example, include an Asian VLBA effort that employs uGMRT as an anchoring station.

Milli-Hz GW observations using space-based interferometric detectors: While continuing its active role in the kHz and nHz GW science, the Indian community should enhance its involvement in the mHz science with LISA which should be taking data in the next decade. Though there is a small community which contributes to LISA science, this can easily be enhanced. LISA data analysis presents new challenges, and the expertise of the Indian GW community can play an important role in this area. Further, early involvement of the Indian astrophysics community working on SMBHs, galaxy evolution, AGNs, etc, in LISA science is highly desirable.

Deci-Hz GW observations using space or Lunar detectors: In the next decade, GW detectors will be observing in the very low frequency (nHz – mHz) and high frequency (Hz – kHz) bands. The missing deci-Hz band that lies between LISA and ground-based detectors is of significant astrophysical importance. The international GW community is actively looking at possible concepts (both space and Lunar-based) for deci-Hz detectors. There is an opportunity for the Indian scientific community to make an early start and to be a leading player in this field. This is also closely aligned with the interest of the IndianSpace Program. A detailed study of the feasibility and the science case will be a good starting point.

VLBI imaging of BH shadows: Another important area where India's gravity community needs to invest more is the strong-field tests of gravity using present and next-generation EHT-like imaging instruments. Besides data analysis, EHT related science crucially needs theoretical development, especially that of models that invoke BH mimickers and BHs in alternative theories. A healthy interface with the theoretical gravity community here should help the Indian community in leading this area of research internationally.

Theoretical modelling of gravitational phenomena: Analytical and numerical modelling of gravitational phenomena is crucial for addressing the open issues in the field. India has traditionally had a strong presence in analytical gravity. Recently, Indian groups have also been involved in numerical simulations, thanks to a new pool of young researchers. Upcoming ground- and space-based GW detectors will require the expected GW signals to be modelled with very high accuracy. This requires a combination of analytical and numerical techniques in GR. Modelling of some of the more complex astrophysical sources such as NS mergers and core-collapse supernovae or SMBH binaries in gas-rich environments requires general relativistic magnetohydrodynamics in conjunction with sophisticated radiation transfer, nuclear physics models, etc. Accurate modelling of shadows of BHs and ultracompact objects for the next-generation VLBI experiments also poses similar challenges and opportunities.

1.11 Cosmology

Cosmology is a research area focused on understanding the origin, evolution, and large-scale structures of the universe, involving interdisciplinary studies encompassing astrophysics, particle physics, and gravity. India has significantly contributed to cosmology, with active involvement in diverse studies like cosmic microwave background analysis, large-scale structure surveys, and major international collaborations such as SKA, TMT, and LIGO.

The paradigm of an epoch of inflation in the very early universe provides a natural framework for understanding the large-scale homogeneity and isotropy of our observed universe and the origin of primordial density perturbations which induce the temperature anisotropies in the cosmic microwave background (CMB) radiation and seed to the formation of large-scale structures in the universe. The simplest models of inflation, which are driven by a single scalar field, lead to a nearly scale-invariant spectrum of primordial curvature perturbations, which are in excellent agreement with the CMB observations. The amplification of vacuum tensor fluctuations during inflation also induces primordial gravitational waves (GW), which leave a clear, but subtle, imprint on the CMB polarization. However, there exists interesting upper bounds on their relative amplitude, characterized by the tensor-to-scalar ratio r. Indian scientists are involved in studying detailed models of inflation, including calculations of higher-order correlations. Precision measurements of CMB polarization from future missions such as CMB-S4, CMB-HD and CMB-Bharat are expected to provide meaningful constraints on these correlation functions as well as r.

The Dark Ages represent the phase of the universe before the first luminous sources (stars, accreting black holes) formed. This phase is best studied using the redshifted 21 cm signal from neutral hydrogen, preferably using a space-based probe. Cosmic Dawn (CD) and Epoch of Reionization (EoR) are some of the least known periods in the history of our Universe. These epochs are marked by the appearance of stars, black holes, galaxies, and quasars, emitting ionizing radiation that transformed the intergalactic medium (IGM). The observations of the redshifted 21-cm signal from neutral Hydrogen atoms (HI) are expected to provide a detailed picture of the CD-EoR. Indian scientists play a significant role in aiming to detect the global 21 cm signal from CD, with the indigenous ground-based SARAS-3 experiment ruling out large amplitude absorption signals and poised to make further important contributions. Besides the radio interferometers, the near-infrared telescopes, e.g., Euclid, James Webb Space Telescope (JWST), and upcoming TMT where India is involved in, will be capable of detecting (via spectroscopy and photometry) the redshifted rest-frame UV light from early galaxies. Additionally, other emission lines, e.g. CII (from ionized carbon) coming from the ISM of these galaxies will be surveyed by next-generation experiments through Line Intensity Mapping (LIM). Strategically conducting 21 cm and CII LIM surveys of the CD over the same patches of the sky will open up a unique opportunity to cross-correlate these observations.

The dark matter paradigm has been firmly established over the last few decades. The microphysical nature of dark matter however remains largely unknown, particularly considering the non-detection of a WIMP-like supersymmetric particle candidate in the LHC. Consequently, alternative theories of dark matter, such as SIDM (Self-Interacting Dark Matter), WDM (Warm Dark Matter), and axions, have garnered significant attention in recent years. The current range of allowed masses for dark matter spans elementary particles that are 10^{-22} eV to $\sim 100 M_{\odot}$ primordial black holes. Astrophysical probes provide some of the most promising avenues to test and understand the nature of dark matter, its mass, thermal properties and interactions. The upcoming decade, i.e., the era of powerful surveys like LSST, SKA, LIGO are bound to push the limits of our understanding in both the large and small scale structure of the universe significantly increasing our ability to pin-down the properties of dark matter.

The discovery of accelerated expansion in the late 1990s led to the introduction of dark energy, represented by a cosmological constant (Λ), to explain the phenomenon. While the Λ Cold Dark Matter (ΛCDM) model became the standard cosmological model, certain discrepancies persist, such as the Hubble tension and tensions in parameter measurements like S_8. As a result, there is a growing need to explore alternative models beyond ΛCDM and constrain them using cosmological probes.

Various models have been proposed in the literature to address the issue of late-time acceleration and investigate the Hubble tension. These models fall into two main categories: dark energy models, where dark energy is phenomenologically modeled, and modified gravity (MG) models, which propose alterations to Einstein's equations through a modified gravitational action. Over the last couple of decades, Indian scientists have actively participated in exploring and studying these intriguing cosmological frameworks.

The evolution of baryons can be useful probe of cosmology. The Lyman-α forest observed in the absorption spectra of quasars can be used to constrain the thermal history of the universe, as well as the power spectrum of matter fluctuations. Access to upcoming facilities, e.g., TMT, would be extremely beneficial to the community in this regard. The Sunyaev-Zeldovich effect, caused by the interaction of CMB photons with baryons in galaxy clusters, induces distortions in the CMB temperature field. Measuring this signal from galaxy clusters can probe the baryons in the Universe, addressing the missing baryon problem and exploring astrophysical feedback mechanisms affecting the distortion around clusters. High-resolution ground-based CMB experiments at Himalayan high-altitude sites offer valuable opportunities for significant science advancements in astrophysics and cosmology.

The total mass of Standard Model neutrinos can be measured through the damping of small-scale fluctuations in the matter power spectrum due to their non-clustering nature. Various cosmological observables, such as CMB lensing, Lyman-α measurements, 21cm intensity mapping, galaxy clustering, cosmic shear, and cross-correlations between them, offer promising avenues for this measurement, making it a major science goal for Stage 4 surveys worldwide, including LSST, Euclid, DESI, CMB Stage 4, and SKA.

Key Science Questions

India's investments in astronomy research and development have nurtured a talented pool of scientists, enhancing global cosmological knowledge and propelling the country as a leader in the field. With the use of the existing and upcoming/proposed facilities, and theoretical studies, Indian astronomers aim to find answers to several key questions. What is the nature of primordial gravitational waves? How and when did stars, galaxies, black holes, quasars, etc form in the era of CD and EoR? What is the solution to the Hubble tension? What is the nature of dark matter and dark energy? What is the solution to the missing baryon problem? Can sterile neutrinos act as Warm dark Matter or fractional Hot Dark Matter?

Recommendations

Access to multi-messenger facilities through continued active involvement in major international projects like the Rubin/LSST, TMT, LIGO and SKA and development of mega facilities in the country such as a 10-12m class optical/IR telescope and eGMRT.

Support and funding for India led experiments such as CMB Bharat and PRATUSH.

Foster collaborations between theoretical and observational cosmologists and encouraging interdisciplinary research with particle physics, astroparticle physics, and astrophysics.

2 Facilities

2.1 Observations

From Galileo's development of the optical telescope in 1609 till today, progress in astronomy is closely intertwined with progress in technology. Breakthroughs in astronomy require increasingly detailed and precise characterisation of ever fainter signals and observations in new or poorly explored parts of the electromagnetic spectrum and of new messengers (i.e. particles and gravitational waves). These are, in turn, enabled by progress spanning a whole host of areas ranging from material science, instrumentation and engineering to signal processing, computing, algorithms and AI/ML. Given their objective, world class A&A observing facilities tend to be at the cutting edge of technologies across multiple domains. In addition to their direct contributions to A&A, the deep engineering and problem solving skills developed in the process of meeting the challenging requirements of these facilities enrich the country's talent pool and lead to the development of indigenous spin-off technologies with potentially large societal benefits.

Global Trends in A&A Observing Facilities Given the rapid pace of advancements in enabling technologies, the upcoming generation of astronomical instrumentation promises a quantum jump in their capabilities. A&A research facilities, especially ground-based ones, have now reached a stage where enabling headline science and improving substantially over existing facilities, requires combined efforts of large international collaborations with a diverse skill set and billion dollar class investments. Also, there are only a handful of locations on the planet suitable for hosting these facilities. At optical and near-IR wavelengths, there have been a few 8-10m class telescopes and several small to medium sized survey telescopes that have come online, bringing in a paradigm change in astronomy in this waveband. The international community is now working towards building three extremely large ground based telescopes (ELTs): the Giant Magellan Telescope (25m primary), the Thirty Metre Telescope (30m primary) and the European Extremely Large Telescope (39m primary). The Legacy Survey of Space and Time (LSST) from the Vera C. Rubin Observatory (8.4m primary), expected to commence in 2025, will revolutionise studies of the deep and dynamic universe. In the radio part of the spectrum, the low- and the mid-frequency telescopes of the Square Kilometre Array Observatory (SKAO) are already under construction and are currently expected to come online in

2028. The *next generation* VLA, which will form the high frequency complement to the SKAO, is in its design phase. Many space-based X-ray and γ-ray observatories are being used to study high energy radiation from astronomical sources, such as Chandra, XMM-Newton, Swift, Integral, NuSTAR, NICER, Insight-HMXT, eROSITA, IXPE and Fermi. Additionally, there are a few ground-based facilities like the MAGIC Florian Goebel Telescopes and the High Energy Spectroscopic System (H.E.S.S) array that are used to study very high energy (VHE) γ-rays. The detection of gravitational waves (GW) by the LIGO Scientific Collaboration in 2016 marked the start of a new era in A&A. The two 4km LIGO detectors in USA and the 3km VIRGO detector in Italy remain operational and have recently been joined by a 3km Japanese detector, KAGRA. Large collaborative efforts are underway to detect the lower frequency GWs using multiple approaches including use of pulsar timing arrays, cosmic microwave polarisation and building space-based GW detectors.

Status of Indian A&A Observing Facilities India hosts multiple very capable ground based observatories - the recently upgraded and globally best-in-class Giant Metrewave Radio Telescope, four modest-size IR and optical telescopes (2.0m to 3.6m), dedicated solar telescopes in optical and radio bands, gamma rays atmospheric Cherenkov telescopes (MACE). India is rapidly establishing itself as a key player among space-faring nations for its ability to build dedicated A&A satellite platforms and pursue science with them. This is exemplified with the success of AstroSat (India's first dedicated Indian astronomy mission aimed at studying celestial sources in X-ray, optical and UV spectral bands simultaneously) that continues to be in operation for over 8 years after launch and the recent spectacular success of Chandrayaan-3, Aditya-L1 (India's first dedicated spacecraft to study the Sun from the L1 vantage point) and XPoSat (India's first and globally the second dedicated X-ray polarimetry mission). India has also established itself as a key player in ground based facilities with its partnership in each of the international A&A Mega-projects – TMT, SKAO and LIGO-India.

Strategic approach for A&A Observing Facilities To place the Indian A&A community on a strong footing to do cutting edge research in the years to come, we need to follow a multi-pronged approach. While on the one hand, we need to ensure that India is a significant partner in key international A&A mega-projects, there is also the need to recognise that for some classes of observatories, there is a considerable gap between the globally best-in-class facilities and those available in India. To address the gap, we need to build the *stepping stones* which will enable us to catch up over time and identify niche areas where we can make a considerable impact. It is also important to acknowledge the fact that for some ground based observatories, India might not be able to offer globally competitive sites. For this, it would be most productive to focus on building the technologies needed for the back-end instrumentation, which can be deployed at the best-in-class telescopes irrespective of their location. Alongside, we also need to maintain and upgrade existing indigenous facilities, and build new ones. These need to be done with the objective of maintaining our lead in areas where we are already globally competitive, and develop competence in areas where we need to catch up. The latter is essential to define the long term path which will enable us to build expertise in areas ranging from engineering and manufacturing to algorithms and analysis, and, in time, evolve into globally leading players and coveted partners. These considerations apply to both ground and space segments and across all cosmic messengers - electromagnetic radiation, gravitational waves and particles.

Recommendations

As has been detailed elsewhere in this document, addressing the fundamental questions in A&A and building a deeper understanding of the Universe require multi-wavelength and often multi-messenger observations. Several recommendations are made regarding facilities that are required for the various science cases, in Section 1. This section summarises the recommendations for observing facilities for the country, that are generic. The recommendations cover the short/near, medium and long term requirements, in no specific priority order. Naturally, observing facilities have to be accompanied by a commensurate growth in the computational facilities (discussed in Section 2.2) and in human resources (discussed in Section 3).

Solar Astronomy: A ground based 2-m optical solar telescope will be the highest priority in the next decade. Smaller telescopes capable of providing full-disk dopplergrams, magnetograms, infrared or optical images of the Sun and coronagraphic images are required for their space weather value and for providing global-scale context to solar space missions. In the short and medium term, augmenting the capabilities of existing radio observatories and putting in coordinated effort across the country to maintain our existing leadership in solar radio science with SKAO precursors and establishing India as the lead for SKAO itself in this science area. For space based facilities, national

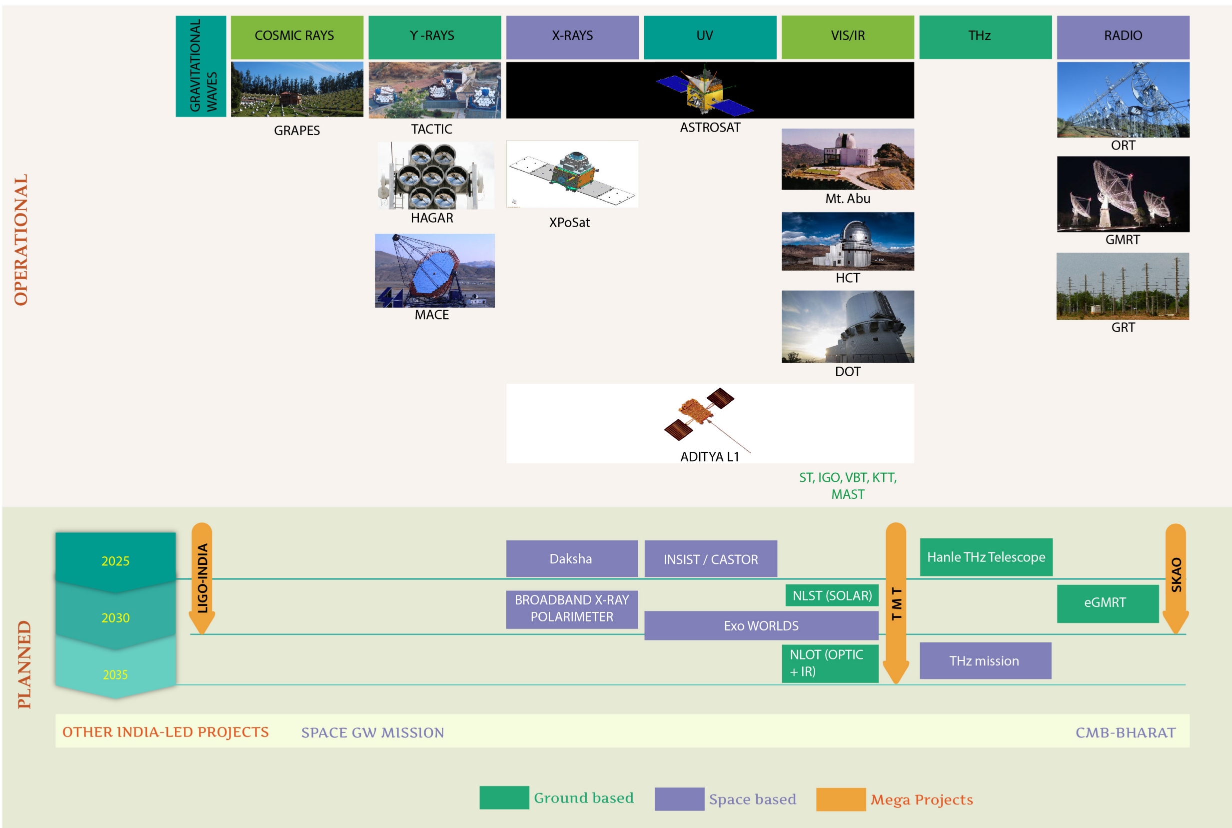

Figure 7: *An overview of the existing and planned ground and space based A&A observatories spanning all messengers, including the international mega-projects in which India is a partner.*

level coordinated efforts are needed to follow up the success of Aditya-L1 and design suitable experiments optimised for space weather studies from L4/L5 or out-of-ecliptic orbits. This will require well planned and multi-faceted short, medium and long term efforts for developing technological demonstrations and proof-of-concept missions from platforms ranging from high altitude balloons and low-earth-orbit missions using cubesats and small satellites to observatory class missions.

γ-ray Astronomy: The near to mid term goals, already initiated, are to augment the ground based gamma-ray atmospheric Cherenkov telescope MACE into an array with two more MACE-like telescopes at Hanle for stereoscopic observations of gamma-ray sources with better flux sensitivity and improved energy and angular resolutions. In addition, it is proposed to set up an array of small-size Schwarzschild-Couder telescopes (SCT) for a wider energy coverage from tens of GeV to a few hundreds of TeV of the gamma-ray sky. The SCTs will enable being a part of the global CTA network. In the long term, enhancing the capability of the GRAPES-3, a particle array detector at Ooty in Tamilnadu to probe the high energy phenomena in the energy range from a few TeV to tens of PeV in the Universe is envisaged, as well as building an array of plastic scintillators and muon detectors at Hanle.

X-ray Astronomy: The success of the AstroSat mission with hard and soft X-ray payloads, and the recent launch of the XPoSat mission have provided a great impetus to X-ray astronomy in India. This needs to be carried forward through the realization of the proposed broad-band, wide field all sky X-ray survey mission *Daksha* within the next 5-7 years, and in the long term, a broad-band X-ray polarimetric mission, with spectro-polarimetric capability. Additionally, it is important to develop technologies for high-energy astronomy in the country in areas such as a) X-ray focusing at energies beyond $\sim$100 keV; b) multilayer mirror fabrication for hard X-ray imaging; and c) new focal plane detectors for imaging such as X-ray CMOS.

Ultraviolet Astronomy: To leverage the expertise gained with the UVIT payload on board AstroSat it is important to have a follow-up UV mission. The proposed 1m class UV telescope, INSIST is one such project. Realization of such a mission within this decade is important as there are no UV missions planned globally in the near future. In the longer term a larger, observatory class UV telescope would be ideal. India may also consider international partnerships in any future UV space telescopes.

Optical-IR Astronomy: Continued participation in the existing and future international projects that the country is already engaged in, such as partnerships in SALT (IUCAA), TMT, MSE (IIA), instrument development for Keck (IIA), etc. In addition, to bridge the gap between the largest telescope currently available in India and the TMT, it is important to build a national 10-12m class telescope (NLOT). A network of small to medium-sized wide-field telescopes will be very useful for time domain astronomy, particularly when LIGO-India goes online. Projects such as the TMT, MSE and NLOT are expected to go online only in about 10-15 years. In the interim period, it is important to utilize the existing facilities in an optimal and efficient manner. Towards this, a common time allocation committee, at least for the 2-4m telescopes, should be considered. Also, efforts need to be made to automate and network the existing facilities. Upgrades and/or augmentation of the facilities to enable this should be undertaken within the next 2-3 years. Network of telescopes can, in the future, also serve as a test bed for the demonstration of optical synthetic aperture telescope using quantum clocks. Design and development of advanced instruments for the existing telescopes such as adaptive optics, multi-object spectrographs, wide-field Optical-IR imaging polarimeter, spectropolarimetry should be taken up. These efforts will bring the expertise to be able to participate in the build of future instruments for the TMT. Some of the existing facilities located at sites that have degraded can be equipped with these modern instruments and re-positioned to undertake large scale survey programmes. India is developing a new base in Antarctica. It is an ideal time to consider siting a 2m class telescope at Antarctica that will, together with the telescopes in India, enable a complete sky coverage. In the space sector, realization of the proposed mega space mission, Exoworlds, will enhance the capabilities.

Sub-mm Astronomy ($\sim$ 30-1000 GHz): Efforts are already underway to carry out multi-year monitoring of multiple Himalayan sites ($\geq$ 5000m) to check for their suitability as sites for sub-mm telescopes. The highest priority in the short and medium term should be to set up a 6-m sub-mm telescope with single-pixel receivers operating at 230/345 GHz and capable backend digital spectrometers with an instantaneous bandwidth of $\sim$4 GHz and a resolution of $\sim$1 MHz at the Indian Astronomical Observatory, Hanle by SAC-ISRO, Ahmedabad. This will be followed by developing higher frequency

($\geq$ 500 GHz) second generation receivers. In the long term, the objective should be to develop a frontier-defining 15 m Indian sub-mm telescope at a high altitude Himalayan site with capabilities to operate up 1.1 THz and join Very Long Baseline Interferometry (VLBI) networks like European VLBI Network (EVN) and Event Horizon Telescope (EHT).

Radio Astronomy: An urgent priority in the short term is to obtain the necessary regulatory and policy support for limiting the Radio Frequency Interference (RFI) in the GMRT region. This is essential for maintaining the performance of the recently upgraded GMRT at levels close to its design specification. The National Supercomputing Mission (NSM) funded commensal observing system at GMRT, called SPOTLIGHT, with petascale computing and storage, with the objective of discovering a large population of FRBs is currently being actively pursued and is expected to come to fruition in the near term. The priority in the medium term should be the expanded GMRT (e-GMRT) facility, which aims to double its collecting area and dramatically increase its field-of-view by using Focal Plane Arrays (FPA). In the long term, the focus would be on developing radio astronomy capabilities in space (such as SEAMS, a research space payload from the university sector) and VLBI (including from space based platforms).

Gravitational Wave Astronomy: In the near term, the efforts towards using Pulsar Timing Arrays, including the Indian Pulsar Timing Array (InPTA; which uses observations from the uGMRT), which have recently yielded the first detection of the Gravitational Wave Background, should be pursued vigorously. A medium term priority should be the timely completion of the 4km arm LIGO-India project, which has recently been approved by the Union Cabinet. Along side, it would be useful to initiate a feasibility study on developing a space-based GW observatory for the DeciHertz band. In the longer term, this study would pave the way for space-based Cosmic Microwave Background (CMB) B-mode polarisation aniostropy experiment named CMB-Bharat and will put India at the forefront of cosmological studies.

New Technologies: It is important for the astronomy community to engage in collaborations in upcoming technology areas. India is already a global lead player in the development of quantum enabled technology. The astronomy community should aim to take advantage of this development, particularly in areas such as development of new detectors, use of quantum clocks for networking of telescopes, use of techniques as light squeezing, development of ”astrocomb” calibration systems, etc.

Globally, efforts are underway to employ AI based technologies for an optimal and efficient use of observing facilities. It is imperative to begin such a development in the country, in collaboration with the industry sector.

Technology hubs/clusters with a focus on overlapping set of problems may be established for development of state-of-the-art instruments for the various astronomy facilities. Such clusters will enable an effective utilization of resources, and also facilitate R&D in the application of new technologies to A&A.

2.2 Computational Astrophysics, Data Science & AI/ML in Astronomy

High Performance Computing (HPC) – the use of a large number of processors in parallel to solve big computational problems – is increasingly playing an important role across a large and diverse range of research areas in astronomy and astrophysics (A&A). The aims of HPC applications range from carrying out simulations for understanding the basic physical phenomena (e.g., the growth and saturation of the magnetorotational instability) to producing mock observables using subgrid physics that can be compared directly with observations (e.g., mock Event Horizon Telescope images from MHD simulations of accretion around black holes, and mock gravitational-wave signals from numerical relativity simulations of black hole binary mergers). Simultaneously, the data gathered by telescopes and generated by massive simulations have grown exponentially and need to be carefully analyzed and organized for their effective future use. Artificial intelligence (AI) and Machine Learning (ML) techniques – which have heavily influenced our daily lives – are increasingly used to quickly discover features in astrophysical images, light curves and spectra, and to characterise, cluster, and classify features, sources and populations.

The Indian astronomy community must stay at the forefront of these exciting developments. For this, we need to constantly adapt our teaching/training of the workforce/students and make available to them the required hardware and software resources. An urgent need is a framework to provide quick and fair access to HPC resources. While the National Supercomputing Mission (NSM) has created a handful of PetaFlop clusters across India, access to these is not through regular calls for proposals. We need to quickly evolve a process for the allocation of national HPC resources through periodic (say, quarterly) calls for proposals that are evaluated by expert programme committees from different relevant research areas. This is close to the procedure followed in more mature HPC ecosystems.

Global Trends in HPC and Astrophysical Research Most advanced nations provide researchers access to state-of-the-art HPC facilities for computational and data-intensive research. Examples for such national programs are ACCESS in the US, PRACE in EU, and similar programs in Japan and Australia. The access to HPC resources are provided via regular tiered calls for proposals that are peer reviewed. Access to advanced computing leads to measurable increase in research impact. Several of the HPC based papers are trendsetting and highly cited in their fields.

Astrophysics is one of the largest application areas of HPC worldwide. Most widely used astrophysical codes are open source community codes such as PLUTO, Athena, Pencil, Ramses, Gadget, Enzo, SpEC, and SpeCTRE. These are extensively tested for their parallel scalability and are being upgraded to run efficiently on hybrid (CPU+GPU) machines. Writing software to efficiently use these hybrid systems requires specialized knowledge of computing and close coordination between hardware, software, and applications teams.

Astrophysical simulations are conducted with the ultimate aim of generating synthetic data for comparison with observations. Large-scale multi-wavelength surveys and targeted observations of specific celestial entities have unveiled the statistical properties and intricate details of various astrophysical phenomena. Unraveling the insights embedded within these observations demands sophisticated numerical simulations capable of accurately replicating and understanding them, a pursuit in which the international computational astrophysics community has made remarkable headway.

However, computational astrophysics encounters a formidable challenge—the vast span of physical scales that must be simulated in both spatial and temporal dimensions. Moreover, the intricate interplay of multiple physical processes, including radiative transfer, chemistry, and plasma transport, which give rise to emission in astrophysical sources, further complicates the computational landscape. Despite this, successful endeavors worldwide have managed to reproduce observations from leading telescopes/instruments.

For example, cutting-edge simulations involve three-dimensional general relativistic magnetohydrodynamics (GRMHD) to study black hole accretion. They accurately replicate Event Horizon Telescope observations of spinning black holes, incorporating the relevant subgrid physics and constraining the model parameters. Equally impressive examples can be drawn from across A&A like simulations of dusty proto-planetary discs and cosmological galaxy formation simulations and gravitational wave signals from numerical relativity. Each of these involve detailed and meticulous accounting of multiple physical effects and post-processing.

Along with the simulations producing ever larger data sets, the landscape of observational data availability has also experienced exponential growth. Technological advancements in telescopes, coupled with leaps in computer technology, have led to the astronomical data deluge. However, the rate of growth in the number of astronomers has not kept pace. Traditional desktop-based data analysis is now inadequate and robust archival practices with pipelined production of advanced data products have become imperative.

Concurrently, the rapid evolution of ML and artificial neural networks has ushered in transformative changes. With increased computing power and access to extensive digital datasets, AI/ML technologies are driving innovations across various domains. Astronomy is no exception, and this is reflected in the number of refereed papers in astronomy (written the world over) based on AI/ML applications, increasing from a mere 14 in 2002 to 824 in 2021. The synergy between AI/ML and high-performance computing is evident, offering benefits in areas such as data fusion, feature extraction, classification, and anomaly detection.

This convergence of advancements — encompassing computational simulations, observational data, data management, and AI/ML methodologies — paints a vibrant picture of a rapidly-evolving A&A landscape.

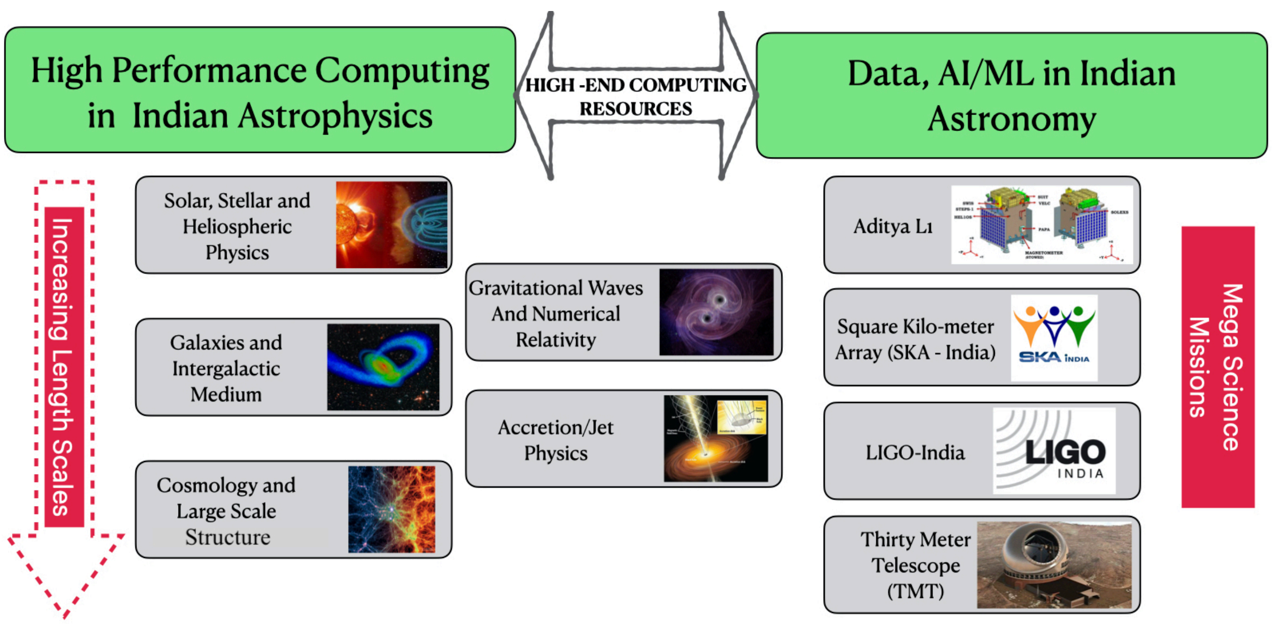

Figure 8: *The current focus of Indian Astronomy and Astrophysics community in terms of application of computational astrophysics, data science and AI/ML.*

Indian A&A Community Using HPC & AI/ML The landscape representing the current focus of Computational Astrophysics and Data Science, AI/ML within the Indian A&A community is depicted in Figure 8. There are computational groups working on different areas of solar physics ranging from the modeling of the solar convective dynamo to the interaction of the solar wind with a planetary magnetosphere, and forward modeling of simulation results to compare with data from instruments like Aditya-L1 and National Large Solar Telescope. Groups are also involved in gravitational wave signal prediction from mergers of compact objects with different orbital and spin parameters. Multiphysics GRMHD simulations with radiative transfer are used to study the physics of accretion on to black holes and neutron stars. Indian groups are also contributing to the development of next generation numerical relativity codes. Several groups are engaged in the simulations of the interstellar, circumgalactic/intracluster and intergalactic medium. Energetic feedback from Active Galactic Nuclei jets and supernovae is simulated at high resolution to assess its impact on galaxy formation. Additionally, hybrid codes have been developed to study particle acceleration processes from cosmic accelerators to understand the origin of high energy particles. On larger cosmological scales, groups are carrying out cosmological simulations of reionization, and growth of galaxies and supermassive black holes to understand the reionization history of the Universe. Indian contributions also shine in domains like solar radio imaging, astrophysical transient detection, and radio astronomy through the integration of automation, AI, and ML techniques.

HPC and big data are important components of international Mega-projects such as SKA, LIGO and TMT that India is partnering in. These observatories will generate massive data which have to be analysed on the fly and only a portion of it, which is scientifically promising, can be saved for future analysis. AI/ML techniques will be crucial to clean the data (e.g., removal of radio frequency interference) and to decide which data to archive.

Recommendations

Specific short, medium and long term recommendations are summarised in Figure 9. These are designed to slowly and steadily enhance national capabilities in the broad area of HPC and Data Science, AI/ML, and their applications in A&A.

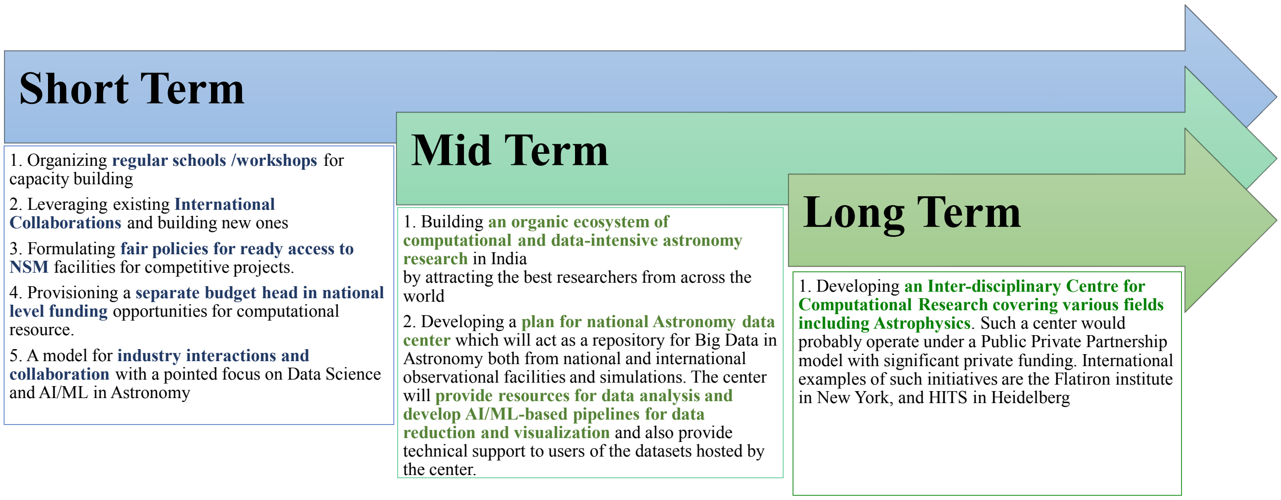

Figure 9: *A summary of recommendations to propel Computational Astrophysics, data science and AI/ML research in Astronomy. They are classified into short-term (5yrs), mid-term (10 yrs) and long term (15-20 yrs) goals.*

The immediate task of the national leadership in HPC should be to provide timely access to reasonable HPC resources to competitive proposals. India's journey towards a reliable indigenous HPC ecosystem, exemplified by the NSM, remains subcritical. A fair and open policy providing proposal merit based timely access to HPC via NSM is essential for India to become a leader in this field. Parallelly, we need to systematically grow the human resource and expertise in these areas. Equally important is to attract top-notch global talent in these areas as scientists and faculty in India. Exploring and building on synergies with domestic and international collaborators will be invaluable.

The skills in HPC, Data Science, and AI/ML are in great demand across sciences and beyond. The workforce we train in HPC/data/AI/ML applied to A&A will have key transferable skills that can be applied to various other sectors. In the long run, this will help forge deeper connections with the industry. It is crucial to expand the coverage of HPC, Data Science, and AI/ML in A&A to universities and institutions without this expertise. For this, computation and ML have to become a part of the standard curriculum in Physics and A&A. This must be accompanied by the creation of a network of the Indian HPC community for easy sharing of expertise and knowledge, fostering deeper collaborations. In this context, partnerships with computer science departments at various institutions will be mutually beneficial. We should explore possibilities such as active collaboration/short-term visits from universities to HPC experts in A&A domain. Periodic workshops on basic HPC and big-data skills followed by more advanced ones will be crucial for the human resource development.

We also need to explore options for formal connections to industry both for knowledge exchange and to secure private funding. In the AI/ML domain, some A&A institutions have already commenced collaborating with the software industry.

It is important to nurture and grow strong citizen science programmes to leverage the large scientifically literate community in our country. For e.g. well designed and curated citizen science projects can yield large and high-quality training dataset, the lack of which often severely limits the application of AI/ML methods or their usefulness.

3 Human Resource Development

Astronomy has been practiced in India from ancient times dating back to 1500BC or even earlier, with major advances made in the 5th and 6th century by Aryabhatta, Varahamihira, Brahmagupta and others. Astronomy continues to thrive in India at the present time with major observing facilities across the electromagnetic spectrum. There are several observatories with excellent facilities, with the GMRT and the space based observatory AstroSat providing world class observations in the radio, X-ray and UV domains, respectively, to the national and international astronomical community. Research and development in astronomy and astrophysics (A&A) is carried out in research institutions like ARIES, BARC, IIA, ISRO, IUCAA, PRL, RRI, TIFR which are either wholly devoted to A&A or have major departments in the subjects. In the recent years, active departments in A&A have developed in several IITs and IISERs, and new facilities and departments have come into being in many universities.

3.1 Growth in Astronomy

A major new development in recent times is the participation of India in multiple international megaprojects in astronomy: LIGO-India for setting up a gravitational wave detector India, the Thirty Meter Telescope (TMT) project for near-infrared and optical astronomy, and the Square Kilometre Array Observatory (SKAO) for radio astronomy. These projects provide Indian astronomers access to cutting edge facilities over the coming decades. In addition, several major ground- and space-based projects are in the pipeline.

There has been a steady increase in the number of researchers in A&A and allied areas. At present, there are about 500 researchers with a regular position in an established organisation, over 100 post-doctoral fellows and 600 Ph.D. students, spread over more than 80 research institutions and university departments. The past 25 years have seen a factor of 10 increase in the number of peer reviewed astronomy publications from the country, as well as a steady growth in the *h*-index (a measure of the impact of the research), as shown in Figure 10. These numbers, based on a search in the Astronomy Database System with *India* in affiliation and restricted to peer reviewed astronomy publications, are a clear indication of the growing impact of India's A&A research globally. The growth is also re-

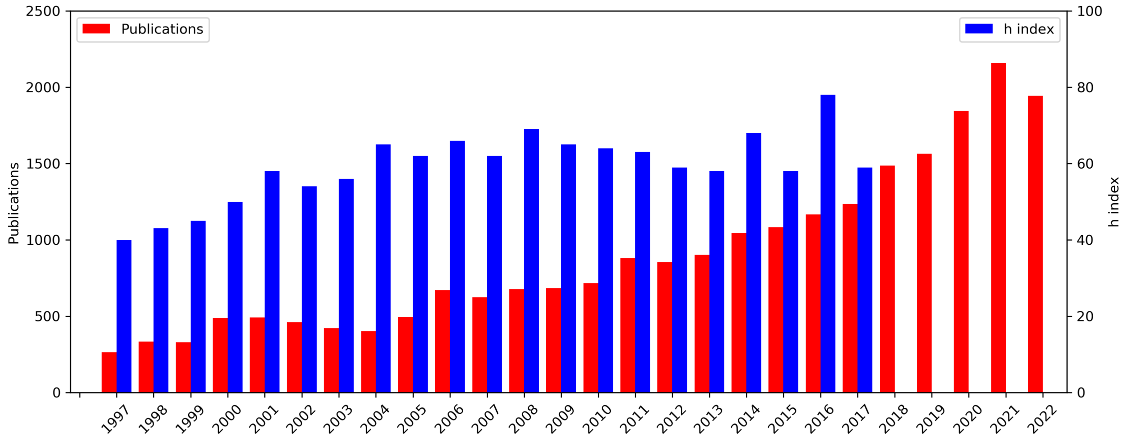

Figure 10: *Number of astronomy publications from India as a function of the year of publication, for the years 1997–2022, shown by red bars. A steady increase in the number of publications is clearly seen. The blue bars show the impact of research being done in India, indicated by the 5-year h-index of these publications. Figure based on peer reviewed publications available in the Astronomical Database System (SAO/NASA ADS) with* India *in affiliation.*

flected in the steady increase in the attendance at the annual meetings of the Astronomical Society of India (ASI). Further, as shown in Figure 11, there has been an increase in the proportion of young researchers, increasing to about 70% during the 2023 annual meeting. Astronomy courses are now offered in more than 25 departments in universities and institutions. Several conferences, workshops and schools are regularly organised and about 500 internships in A&A are available for aspiring students every year. While all of these are extremely encouraging, it is important to increase the numbers and widen the organisations with A&A research to enable a vibrant and competitive community that can optimally use the national and international facilities, and carry out research with a significant global impact.

3.2 Capacity building

Astronomy is fascinating to people of all ages and from all walks of life. Public lectures in astronomy, sky watching and telescope making sessions, programmes built around special astronomical events etc. always draw an excellent response. Public outreach activities conducted by professional

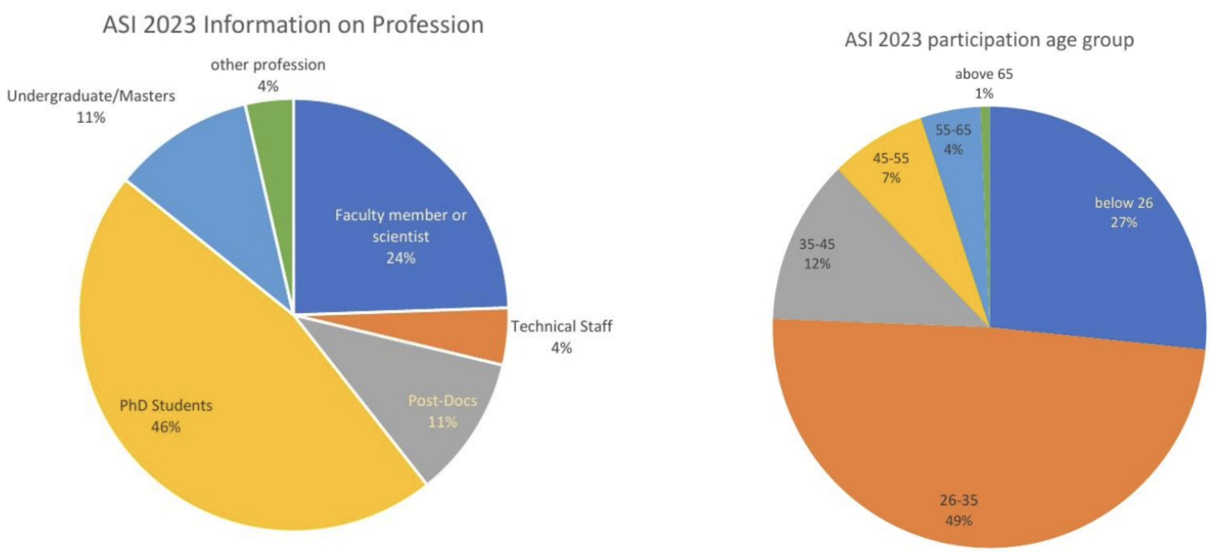

Figure 11: *Demography of astronomers in the country based on participation in the 2023 annual meeting of the Astronomical Society of India.*

astronomers, institutes, university and college departments, planetariums, amateur astronomy groups and others have been reaching out very effectively to all sections of society including the public, schools and college students and teachers, amateur astronomers and so forth. Several astronomy institutes now have public outreach departments and the ASI has a Public Outreach and Education Committee (POEC) which is very active. Many school and college students exposed to astronomy through public outreach take up studies and careers in astronomy.

Beyond outreach, further efforts are needed to seriously involve undergraduate and postgraduate students in more formal training in theoretical, observational and instrumentation aspects of astronomy. The most important way for this is to introduce formal courses in A&A at the undergraduate and postgraduate levels, in science as well as engineering streams. Such courses are now a part of the curriculum in IITs, IISERs and a small number of universities, but they need to be taught much more widely. That will need a large number of teachers who themselves specialise in A&A, creating job opportunities. The teachers would be engaged in research in A&A, which will again help in widening the spread of high quality A&A research in the country. Since it will take a while for a high quality teaching ecosystem to develop across the country, the classroom teaching can be supplemented by material from NPTEL and other Swayam platforms. Extremely important will be regular workshops, schools, internships, observing programs at observatories and other such activities for undergraduate, postgraduate as well as research students, conducted by expert astronomers. A particularly successful initiative for introducing undergraduate students to research in astronomy has been the National Initiative on Undergraduate Science (NIUS) programme of HBCSE-TIFR. The long term nature of NIUS projects allows students to explore the depths of a problem, and exposes them to a variety of challenges of modern research. Such extended nurture programmes complement the short term project experiences of students. The aim of all these exercises will be to produce well trained and capable students motivated to work on challenging problems in front-line theoretical, observational and instrumentation areas.

Cutting edge work in A&A requires skills in data analytics, high performance computing (HPC) and Artificial Intelligence (AI). Capacity building programmes should provide advanced courses in these areas too, which will in fact make them doubly attractive to students and young researchers, who will develop skills which would provide them career opportunities outside the areas covered by A&A as well. Collaborative projects between leading astronomers in the country and students and faculty in universities and colleges, have proven to be very effective for capacity building, especially in observational areas. Recent significant examples come from AstroSat, where collaborative programmes have been undertaken through accepted proposals for observing time. Some of these proposals have been led by the university community and publications in leading journals like Nature have had university students as first authors.

3.3 Career Opportunities in Astronomy

The past decade has been extraordinary for achievement in A&A with six Nobel prizes awarded to astronomy-related discoveries. We expect this to grow further with megaprojects and big data for at least the next few decades. Indian scientists have shown their active presence in some of these frontier areas. To further utilize the interest in A&A, which has grown in the past few decades, there is an urgent need to have departments and open positions in A&A at various levels in all academic places including colleges, universities, and research institutes. Some IITs have new departments in space science and astronomy, but such departments are needed in other technology institutions and IISERs as well. An increase in hiring at faculty level is required across institutions along with some flexibility in hiring to be able to attract the best talent. A&A is inherently interdisciplinary, routinely relies on big-data and numerically intensive computing. Thus, the A&A departments will be able to contribute to the teaching and development for the whole university in very useful areas like high end computing, data analytics and AI.

The current number of postdoctoral fellows in the country is extremely low. There is a need for the creation of a large number of postdoctoral positions spread across the country as avenues for research students after their Ph.D. Some of these positions can be supported by central schemes like SERB National Post-Doctoral Fellowship (NPDF), UGC D.S. Kothari fellowship in sciences, CSIR Research Associateship (CSIR RA), SERB Women Scientist Scheme (WOS) etc. It is necessary to have some postdoctoral fellowship schemes devoted to A&A.

Public outreach programmes in A&A also offer attractive employment avenues for young persons trained in astronomy who wish to look beyond research and teaching positions.

In all of these efforts, it is important to maintain a healthy gender balance and diversity through conscious efforts.

3.4 Human Resources Growth Avenues in Industry

Traditionally, astronomers with expertise in software development or instrumentation could be absorbed by the industry. The industry now has requirements for young researchers with much wider skill sets, including mathematical physics, statistics, data analytics, and AI. Expertise in Deep Learning and related techniques is greatly in demand across the entire spectrum of industries. In a parallel development, large knowledge-based industries are exploring avenues for projects in space technology. Such projects need researchers who are adept at space instrumentation, advanced image processing, celestial mechanics, and so forth. The involvement of the industry sector in these programmes is expected to increase greatly over the coming decade, putting astronomers with the required skill sets in a very advantageous position for industrial employment. The number of students, young researchers, and engineers needed on various projects in astronomy, particularly the megaprojects which are already approved or are in the pipeline, is much larger than the number which can be absorbed in research or academic institutions. But, given the industry's need for the skills these young people have, there is much opportunity for them to engage in interesting, challenging and well-paying careers to which they earlier had no access. Systematic effort is however needed to turn this potential into reality.

3.5 Recommendations

Widen the reach through an increased number of A&A departments in science and technology research institutions and institutions of higher learning.

Include A&A courses at the undergraduate and post-graduate level to facilitate a career in astronomy.

Include also UG/PG/Ph.D. in Astronomy in the minimum eligibility criterion for several entrance examinations and job advertisements.

Increase the number of A&A positions at all levels including faculty, research scientists, post-doctoral fellows and students with flexibility in hiring.

Mega-science projects should run dedicated training programs at the postgraduate and Ph.D. level.

Funding avenues for lectures by A&A experts in Universities, workshops/schools for undergraduates and post-graduate students, meetings for researchers covering topics as data analytics, HPC and AI.

Provide funding support for dedicated short-term research projects at the observational facilities.

Continue and grow outreach efforts to reach a larger fraction of the young student population.

Increase the scope of science-industry joint ventures to help capacity building at both the fronts.

4 Astronomy & Society

Astronomy is a "gateway science", in that it links to almost every branch of science and has an unparalleled inspirational potential that can attract students to STEM as well as promote scientific temper within the public at large. Hence, the relation between astronomy and society is far too important to be neglected. The Indian A&A community is already engaged in outreach and science communication through the activites of the ASI's POEC and the outreach and science communication programmes of a multitude of organisations and individuals across the country. In addition to promoting science and scientific temper, astronomy also has other societal impacts, such as in areas of heritage, sustainable development, diversity and inclusion, etc. All of these are addressed here, with suggestions for a continued and effective engagement in the future.

Outreach and Communication is a key component, which is practised by a number of stakeholders. Many institutes now have full-time staff for this purpose, who regularly communicate recent research and organise outreach programs. This activity has grown in recent times, and should be encouraged for further growth. Planetaria and science centres cater to lakhs of people every year and their connection with researchers needs to be strengthened, including with amateur astronomers. India is a global exemplar in public engagement activities during celestial events, and better coordination between stakeholders will be useful. Relations between the media and the astronomy community are healthy and growing, but this needs more attention, including private media. Science communicators across India have created imaginative resources (posters, models, demos, talks etc) in many languages over the years that are being used widely. Interest in citizen science is increasing in urban areas, and new citizen science projects, based on data and tools from India also exist. Tremendous work has been done over decades in promoting scientific temper in the society at large by explaining the origin of various astronomical events and phenomena. These efforts need to be enhanced to have a wider reach and penetration within the society.

The subject of astronomy affords huge potential for **education**. The lack of astronomy in a substantive way in school curricula has been lamented about for decades, but not much progress has been achieved. In early education, the connection between astronomy and daily lives (e.g. calendars, festivals, tides etc) can be highlighted. In the higher grades, astronomy's connection to topics studied (e.g. optics, circular motion) can be introduced. Practical astronomy in schools, emphasized by NEP 2020, should be encouraged through the provision of telescopes and computers for this purpose. Research in Astronomy Education, undertaken by HBCSE-TIFR, and the newly formed IAU OAE India Centre, for example, can provide valuable inputs towards this initiative. Avenues like the Olympiad and summer courses in planetaria have attracted motivated students over the years and can be scaled up.

History and Heritage is an important part of astronomy, and the long tradition of astronomy in India has been subject to study by a number of individual experts over the years. Our vast material heritage in the form of manuscripts, especially in Sanskrit, have been translated and analysed by many scholars, though comparable efforts for those in other languages are needed, including in areas like navigation. The most famous heritage sites are the Jantar Mantar observatories. Considerable efforts have been devoted in recent years towards recreating a detailed understanding of the instruments at these observatories and sharing this information broadly to encourage the public to carry out these observations themselves. Astronomical connections also exist for numerous other monuments like temples, caves, gardens, etc. While there has been some ongoing research in this area, it needs to be developed and strengthened further. Additionally, research into astrolabes, stone inscriptions, megalithic alignments, etc. needs to be initiated before the information they provide are lost. Some work has also started on compiling astronomy content in folklores, stories and myths, especially from oral history of indigenous communities. A network of experts on linguistics, Indian mathematical methods and history, in addition to astronomers, needs to be formed to make further progress.

Astronomy for Development is a topic that is actively pursued globally, led by the work of the IAU OAD. A fast growing field is that of astro-tourism that is being developed around dark sky sanctuaries, which preserved the darkness of skies, including around observatories, and in turn uses it for astronomy based tourism that benefits the local communities. The Hanle Dark Sky Reserve in Ladakh, centered around the Indian Astronomical Observatory (operated by IIA) is the first such example in India. Preserving dark skies for optical astronomy, both professional and amateur, and radio-quiet environment for radio telescopes is essential. Many amateur astronomers have also been creating a number of astronomy start-ups which conduct outreach and education events as a monetized enterprise. Some have also started telescope dealerships. Another area of interest is using techniques of astronomy like image analysis, machine learning, and big data science, in other fields like biology, as is being done by the Pune Knowledge Cluster.

Our astronomy community aspires to incorporate diversity, equity, and inclusion in its functioning as we look to the future. This entails building an equitable community and many studies have shown that not only does unconscious bias exist within science communities, but also that increasing equity and diversity results in a betterment in the quality of work. Following the lead of ASI's Working Group for Gender Equity (WGGE), it is time we turn our attention to under-representation in terms of other axes like caste, region, religion, special abilities, sexual orientation etc, within the framework of the prevailing laws and guidelines. This needs quantitative data as well as inputs from social scientists on structural issues. The diversity of ASI attendees is indeed increasing on certain axes like work location, university participation etc. Outreach by POEC and others are increasingly becoming multilingual, but catering to disabilities using haptic and sonification technologies is still nascent in India. Conferences as well as outreach events need to be consciously designed to minimise the many barriers for participation. The inspirational potential of astronomy knowledge in promoting equity, peace and global citizenship is an area with great potential that can be made use of within the Indian context.

Special purpose centres and personnel for EPO at research institutions are increasing, but needs to be expanded much further, especially given the number of mega-projects being undertaken by Indian astronomers. "Scientific Social Responsibility" mandates that science communication and outreach be seen as an integral part of an institute's functioning as well. Outreach personnel are mostly taken at a junior level but usually also require a PhD, which eliminates outreach experts who are older or have been doing great work but without a PhD. Hence, the hiring policy needs to be more flexible and the career progression, including assessment schemes, of such personnel needs to be clearly defined. The personnel also need to be trained and networked with each other.

4.1 Recommendations

Several aspects and areas that connect the society at large with astronomy have been discussed. Based on these discussions, we provide here a set of recommendations that will enable further engagement in these areas.

- Training programmes and academic exchange opportunities (like conferences) should be instituted for astronomy outreach personnel from formal (e.g. institute staff), informal (e.g. amateurs) and private (e.g. journalists) sectors.
- Encourage creation of local hardware (e.g. mobile planetaria) and resource materials with a special emphasis on communication in regional languages.
- Keeping in mind the recommendations of NEP 2020, create a model curriculum for school level astronomy and associated materials. Learning through doing, including handling of small telescopes, should be encouraged. Astronomy may also be offered as an optional subject at the secondary school level.
- Create a pan-India virtual hub to coordinate studies and knowledge exchange on history of Indian astronomy with adequate funding support.
- Create dark and/or quiet sky sanctuaries around major astronomical observatories in the country, and dark sky parks near urban hubs.
- Diversity, Equity and Inclusion processes within the astronomy community along different axes should be routinely documented, quantified and reflected upon for continuous improvement.
- All research centres should have a dedicated astronomy education and outreach division with flexible hiring and career advancement policies, which take into account the unique landscape of these activities.
- Create an inter-disciplinary hub for research in the history of astronomy and astro-archaeology with support for collection, preservation, and digitisation of material.

List of Abbreviations

A&A - Astronomy and Astrophysics

AGB - Asymptotic giant branch star

AGN - Active galactic nuclei

AI - Artificial intelligence

ALMA - Atacama Large Millimeter/submillimeter Array

AO - Adaptive Optics

ASI - Astronomical Society of India

BH - Black holes

BnBH - Binary black hole

BNS - Binary Neutron stars

CBSE - Central Board of Secondary Education

CGM - Circumgalactic medium

CMB - Cosmic Microwave Background

CME - Coronal mass ejection

CMOS - Complementary metal-oxide semiconductor

CO - Compact objects

CTA - Cherenkov Telescope Array

CV - Cataclysmic variables

DECIGO - Deci-hertz Interferometer Gravitational wave Observatory

DEI - Diversity, equity, and inclusion

DESI - Dark Energy Spectroscopic Instrument

DM - Dark matter

DOT - Devasthal Optical Telescope

ECR - Early Career Researcher

EHT - Event Horizon Telescope

EPO - Education & public outreach

ELT - Extremely Large Telescope

EoS - Equation of state

eROSITA - extended ROentgen Survey with an Imaging Telescope Array

ESA - European Space Agency

ESO - European Southern Observatory

FPGA - Field programmable gate arrays

FRB - Fast radio burst

GAIA - Global Astrometric Interferometer for Astrophysics

GMRT - Giant Metrewave Radio Telescope

GPU - Graphics processing units

GR - General relativity

GRAPES-3 - Gamma Ray Astronomy PeV EnergieS phase-3

GRMHD - General Relativistic Magnetohydrodynamics

GROWTH - Global Relay of Observatories Watching Transients Happen

GW - Gravitational wave

HabEx - Habitable Exoplanet Observatory

HB - Horizontal branch

HCT - Himalayan Chandra Telescope

HMXT - Hard X-ray Modulation Telescope

HPC - High performance computing

H-R Diagram - Hertzsprung–Russell diagram

IAU - International Astronomical Union

IFS - Integral field spectroscopy

IFU - Integral field unit

IGM - Intergalactic medium

ILMT - International Liquid Mirror Telescope

IMF - Initial mass function

INSIST - INdian Spectroscopic and Imaging Space Telescope

IR - Infra-red

IRIS - Interface Region Imaging Spectrograph

ISM - The interstellar medium

IXPE - Imaging X-ray Polarimetry Explorer

JUICE - Jupiter Icy Moons Explorer Mission

LIGO - Laser Interferometer Gravitational-Wave Observatory

LISA - Laser Interferometer Space Antenna

LSST - Legacy Survey of Space and Time

LUVOIR - Large Ultraviolet Optical Infrared Surveyor

MC - Magellanic clouds

MHD - Magnetohydrodynamics

ML - Machine learning

MOS - Multi-object spectroscopy

NEO - Near Earth Objects

NEP - National Education Policy

NICER - Neutron Star Interior Composition Explorer

NIUS - National Initiative on Undergraduate Science

NLOT - National Large Optical Telescope

NLST - National Large Solar Telescope

NPTEL - National Programme on Technology Enhanced Learning

NS - Neutron stars

NSM - National Supercomputing Mission

NuSTAR - Nuclear Spectroscopic Telescope Array

OAE - Office of Astronomy for Education

ORT - Ooty Radio Telescope

pAGB - post Asymptotic giant branch

PHO - Potentially Hazardous Objects

PTA - Pulsar timing arrays

PLATO - PLAnetary Transits and Oscillations of stars

POEC - The Public Outreach & Education Committee

QPO - Quasi-periodic oscillation

RFI - Radio Frequency Interference

RV - Radial velocity

SCT - Schwarzschild-Couder telescopes

SFR - Star formation rate

SKA - Square Kilometre Array

SKAO - Square Kilometre Array Observatory

SLR - Short-lived radionucleides

SMBH - Super Massive Black Holes

STEM - Science, technology, engineering and mathematics

TESS - Transiting Exoplanet Survey Satellite

TMT - Thirty Meter Telescope

TPU - Tensor processing units

UGC - University Grants Commission

UV - Ultra-violet

UVIT - UV Imaging Telescope

VBT - Vainu Bappu Telescope

VLT - Very Large Telescope

VLBA - Very Long Baseline Array

VLBI - Very Long Baseline Interferometry

WD - White dwarfs

WGGE - Working Group for Gender Equity

XPOSAT - X-ray Polarimeter Satellite

4MOST - 4-metre Multi-Object Spectroscopic Telescope

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Shrivastav, A. M. (IOP)
Shrivastav, Arpit Kumar (ARIES)
Shukla, Amit (IIT-Indore) [WG7]
Shylaja, B. S. (JNP, Bengaluru) [WG16]
Singh, Gaurav (IIA)
Singh, Krishna Kumar (BARC)
Singh, Nishant (IUCAA) [WG14]
Singh, Veeresh (PRL) [WG6]
Sinha, Akriti (IIT-Indore)
Sivarani, T. (IIA) [WG3, WG5]
Soam, Archana (IIA)
Souradeep, Tarun (RRI) [WG11]
Sreekumar, P. (MAHE)
Srianand, R. (IUCAA) [WG6]
Srivastava, Abhishek K. (IIT-BHU) [WG1]
Stalin, C.S. (IIA) [WG7]
Sule, A. (HBCSE) [WG15]
Sur, Sharanya (IIA) [WG6, WG12]
Surnis, Mayuresh (IISER-Bhopal)
Sutaria, Firoza (IIA)
Tej, Anandmayee (IIST)
Tendulkar, Shriharsh (TIFR) [WG8, WG9]
Tripathi, Durgesh (IUCAA) [WG1]
Uddin, Wahab (ARIES)
Vadamattom, Veena (MPIfR, Bonn)
Vadawale, Santosh (PRL) [WG13]
Vaidya, Bhargav (IIT-Indore)
Vemareddy, P. (IIA) [WG1]
Venkataramani, Kumar (PRL)
Vichare, Geeta (IIGM)
Vig, Sarita (IIST) [Coordinator & Editor]
Vigeesh, Gangadharan (AIP, Germany)
Vir Lal, Dharam (NCRA) [WG6]
Vivek, M (IIA)
Wadadekar, Y. (NCRA-TIFR)
Yadav, Kuldeep (BARC)
Yadav, Nitin (IISER-Tvm) [WG1, WG12]
Yadav, V. (ARIES) [WG16]
Yadav, Vipin K. (ISRO-VSSC)
Yerra, Bharat Kumar (IIA) [WG5]